USEFUL INFORMATION FOR ENGINEERS

SECOND SERIES

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USEFUL

INFORMATION FOR ENGINEERS

CONTAINING EXPERIMENTAL RESEARCHES ON
THE COLLAPSE OF BOILER FLUES AND THE STRENGTH OF
MATERIALS, AND LECTURES ON POPULAR EDUCATION AND VARIOUS SUBJECTS
CONNECTED WITH MECHANICAL ENGINEERING, IRON SHIP-
BUILDING, THE PROPERTIES OF STEAM, ETC.

BY

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Member of the Royal Academy of Turin, &c.

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1860

TO

MAJOR-GENERAL EDWARD SABINE

R.A., D.C.L., F.R.S., F.L.S.

Hon. Mem. Cam. Phil. Soc., Ord. Boruss. '*Pour le Mérite*' Eq. et Acad. Reg. Berol.,
Acadd. Imp. Sc. Petrop., Brux., Norv., etc.

This Second Series of Lectures is Inscribed

BY THE AUTHOR

AS A MARK OF PERSONAL ESTEEM

AND AS A TESTIMONY TO HIS EMINENT SCIENTIFIC ATTAINMENTS AND

DISTINGUISHED SERVICES IN THE

PROMOTION AND EXTENSION OF USEFUL KNOWLEDGE

PREFACE.

THE great success which has attended the issue of the first series of Lectures, under the title of Useful Information for Engineers, has induced me to publish the present volume, in which will be found various original papers not before printed, or not easily accessible to ordinary readers.

In the discourse on the education of working men, I have shown what a wide field is still open for talent combined with industry and perseverance in the attainment of distinction in science and art. I have not hesitated to encourage the young aspirant to prepare himself by mental culture and vigorous exertion for the realisation of an honourable name in the voyage of life. To awake an honest ambition, and to render sensible latent talents, were the objects of various addresses delivered from time to time in various Institutes, and I flatter myself that the reader will not blame me for seeking to give a wider circulation and a more permanent value to such an attempt than was possible in an oral lecture. I hope that in stimulating working men to cultivate their powers to the highest point of development, I have not ventured beyond professional duty, and that the reader will sympathise with

me in the wish to raise the working men of this kingdom to a higher state of intellectual culture than they have heretofore attained in their relations to society and the domestic circles by which they are surrounded.

Leaving, however, the question of popular education to abler hands, I would now direct attention to the papers on the Collapse of Tubes, in which will be found not only the first investigation of the conditions of rupture in vessels exposed to uniform external pressure, but also an entirely new law of resistance, fully determined by direct experiments. The results recorded in these papers bear directly on the daily practice of the Engineer. The law that the resistance is inversely as the length of the tube exposed to pressure, is both of great importance and wide application; in a word, it should be kept in view in every construction where tubes exposed to external pressure form the whole or a part of the design.

In the paper on the Resistance of Glass Globes and Cylinders to Collapse from External Pressure, and on the Tensile and Compressive Strength of various kinds of Glass, I have sought to confirm the previous experiments on wrought iron tubes, by experiments on a perfectly homogeneous material. At the same time, as the mechanical properties of glass have been hitherto little known, the paper has been rendered more complete by experiments on the tensile and compressive strength, which I hope may prove valuable to those who are engaged in scientific investigations. We are still very deficient in our knowledge of the laws of contraction in bodies passing from the fluid to the solid state, and the effect of internal strains arising from unequal contraction on the cohesive strength

of the material. That such strains exist to an injurious extent is often seen in cast iron, and was found to exist to a still greater extent in the experiments on glass. Let us hope that further researches may be made on this point, and greater certainty secured in metallic constructions, under the influence of temperatures producing in succession the fluid, the semi-fluid, and the solid state.

On the influence of temperature on the cohesive strength of wrought iron I made, some time ago, the experiments recorded in the succeeding paper. These extend from below zero to a dull red heat, and will, I trust, be found of value in showing the conditions in which the material can be trusted when exposed to increased or diminished temperatures.

I have reprinted the paper on the Compressive Strength of Brick and Stone for the guidance of the engineer and architect, and they may safely be relied upon in calculating the strength of piers, walls, and other structures where these materials are employed.

The Lecture on the Machinery employed in Agriculture was undertaken at the request of several distinguished agriculturalists, and amongst them the Right Honourable the Speaker of the House of Commons. In this brief treatise I have endeavoured to point out the defects of our present improved and improving system, and to propose remedies for them. I have especially urged upon the farmer the value and necessity of machine culture, in order to increase the productiveness of the soil, and to secure the crops with greater certainty and despatch. I have directed attention to the state of the land, and the improvements required before machine culture can be effi-

ciently employed, and I have concluded with the expression of a belief that the English agriculturalist might be very much benefited by availing himself of the appliances which the present advanced state of mechanical science has placed at his disposal.

The Lectures on the Rise and Progress of Civil and Mechanical Engineering were intended for the information and encouragement of the members of several combined institutions at Derby; they are historical and descriptive, and having been personally concerned in the promotion of some of the works described, I am perhaps better able to supply the material and fill up the gap between the present and that period which belongs to the past history of engineering art.

The Lectures on Iron Shipbuilding are on a question of such deep importance that I make no apology for their introduction into this series. When it is known that the most disastrous and fatal consequences have followed from the construction of vessels on erroneous principles, and that thousands of lives are at the mercy of our naval engineers and architects, assuredly it is essential to the interests of humanity that defects and errors of construction should be pointed out and sounder principles applied. If we examine closely into the state of iron shipbuilding, it will be found that numbers of vessels are built and are now afloat which are perfectly unseaworthy, that our knowledge of first principles is far from perfect, and that a remedy should be immediately applied to avert the calamitous and fatal shipwrecks which so frequently fill the columns of the public prints.

Impressed with the conviction that these lamentable

catastrophes might be in some cases averted, I was induced to venture on the inquiry, and finding that a want of foresight in the builder, or a want of knowledge of the conditions of rupture of iron vessels on the present principle of construction appeared to exist, I lost no time in applying the results of my own experiments on girders to this case, and submitted my conclusions to the shipowners of Liverpool and the members of the Polytechnic Institute of that town. The same paper was subsequently read before the Institute of Naval Architects in London, and forms the fifth lecture of the present volume.

In the sixth lecture I have applied the same principles to vessels of still larger size, where a modified form of construction appeared necessary. I earnestly hope that the views thus recorded may lead to further inquiry, and subsequently to a class of experiments calculated to ensure safety, and that with a more correct and judicious distribution of the material and more exact principles of construction.

It was originally my intention in the publication of this series to have resumed an inquiry into the properties of steam. This experimental investigation has occupied my attention, along with that of my friend and colleague Mr. Thomas Tate, for the last three years, and although we have arrived at important results in regard to density and expansion, up to 60 lbs. pressure per square inch, we are short of data for extending them to higher pressures and a greater degree of superheating, and the experiments, although in progress, are not yet in a condition suitable for publication. A *résumé* of the results already obtained will, however, be found embodied in Lecture VIII., ex-

tracted from our joint paper in course of publication by the Royal Society.

Amongst other constructions of a useful and practical character, I have introduced a description of the tubular cranes, so admirably adapted for lifting heavy goods, and swinging them round over a circle of large radius.

In this statement it now only remains for me to express my acknowledgments to the Councils of the Royal Society and the British Association for the Advancement of Science, for the readiness with which they granted permission to republish some of my papers in the present volume. Also to my friend Mr. T. Tate, who is ever willing to assist me with his superior mathematical attainments. I am indebted to my assistant and secretary, Mr. W. C. Unwin, for the care he has bestowed on reading the proofs and preparing the illustrations. And in conclusion, I may express the wish that the present volume may be found as useful and acceptable to a numerous body of readers as I believe its predecessor has already proved itself.

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PART I.

EXPERIMENTAL RESEARCHES.

I. RESEARCHES ON THE RESISTANCE OF CYLINDRICAL VESSELS OF WROUGHT IRON TO COLLAPSE.

(Reprinted from the Transactions of the Royal Society, 1858.)

THE following experiments were undertaken at the joint request of the Royal Society and the British Association for the Advancement of Science. Their object is to determine the laws which govern the strength of cylindrical vessels exposed to a uniform external force, and their immediate practical application in proportioning more accurately the flues of boilers for raising steam, which have hitherto been constructed on merely empirical data.

It is well known that the immense extension of the application of steam power, and the consequent inducement to economise as far as possible the fuel necessary for its production, together with the growing tendency to employ the expansive principle, has caused a general increase of the working pressure from 10 lbs. to 50 lbs., and even in some cases to 150 lbs. on the square inch. Unfor-

tunately, however, our knowledge of the principles of construction has not kept pace with our desire to economise, and hence the change has been accompanied by an increase of dangerous and fatal accidents from boiler explosions. Investigation has frequently shown these lamentable catastrophes to have arisen from ignorance of the immense elastic power of steam, and from a want of knowledge of the forms of construction best calculated to retain an agent of such potent force; and as explosions become more frequent in proportion as the pressure is increased, it is the more necessary to inquire into the causes of such disasters, and to apply such remedies as may effectually prevent them.

In order to save space, and to increase the generative powers of boilers, *internal flues* and tubes have been generally adopted, and that without sufficient attention to proportioning their diameter, length, and thickness of plates, so as to ensure safety on the one hand, and economy of material in its judicious distribution on the other. Hitherto it has been considered an undisputed axiom among practical engineers, that a cylindrical tube, such as a boiler-flue, when subjected to a uniform external pressure, was equally strong in every part, and that the length did not affect the strength of a tube so placed. But although this rule may be true when applied to tubes of indefinite length, or to tubes unsupported by rigid rings at the extremities, it is very far from true where the lengths are restricted within certain apparently constant limits, and where the ends are securely fastened in frames, which prevent their yielding to an external force.

In some experimental tests to prove the efficiency of some large boilers, the author had some misgivings as to the strength of the internal flues to resist a force tending to collapse them. In these experiments it was found that flues of 35 feet long were distorted with considerably less

Plate I.

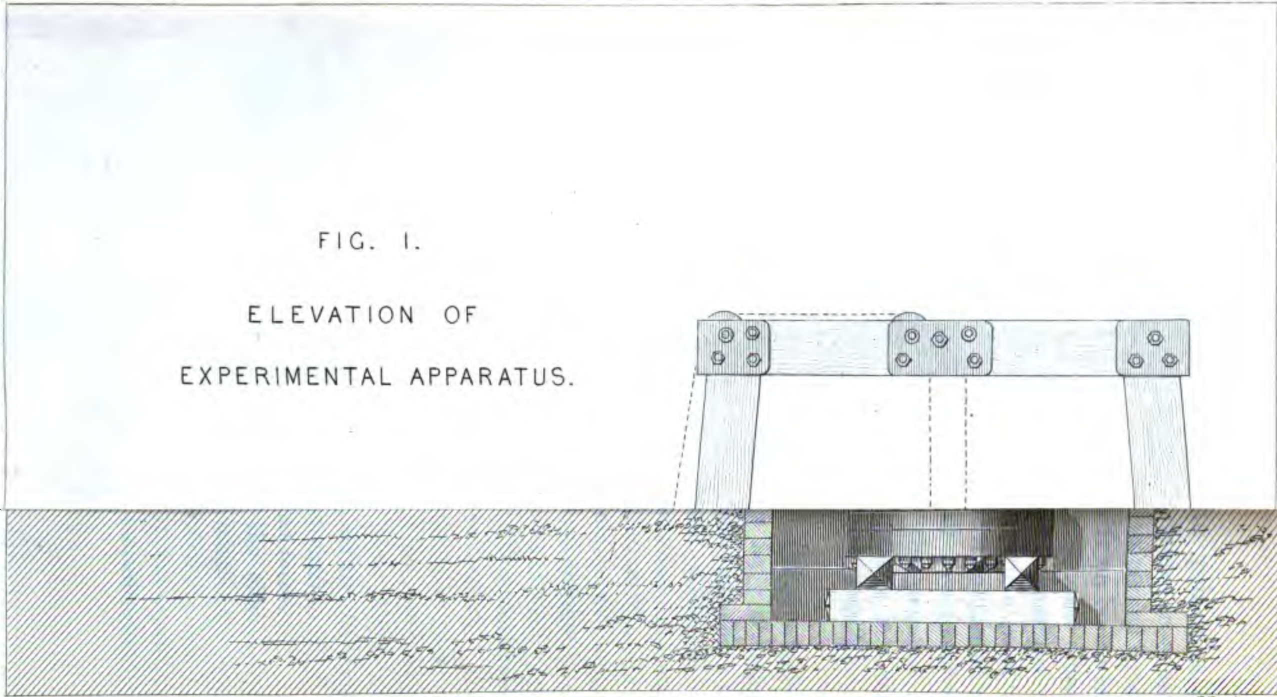


FIG. I.

ELEVATION OF

EXPERIMENTAL APPARATUS.

J. Basire, sc.

force than others of a similar construction 25 feet long. This anomalous result led to further inquiry, which being far from satisfactory, the present series of experiments were instituted, with, it is believed, very conclusive results.

In order to have every facility for conducting these experiments, application was made to the Directors of the North-Eastern Division of the London and North-Western Railway, for permission to conduct them under their large octagonal engine-house at Longsight, near Manchester, where the necessary pumps and cranes were at hand. To this request the Directors gave their cordial assent, and in this position I had the benefit of the suggestions and experience of Mr. J. Ramsbottom, the Company's engineer, and also the constant attendance of Mr. R. B. Longridge, the engineer, and chief inspector to the Association for the Prevention of Boiler Explosions. To both those gentlemen I tender my best acknowledgments for the able and efficient assistance I have received from them during the whole time occupied in conducting the experiments.

To attain the objects of the experiments in a satisfactory manner, it was necessary that the apparatus should be of great strength and of dimensions capable of receiving tubes of considerable length and diameter. For this purpose a cast-iron cylinder was prepared, 8 feet in length, 28 inches in diameter, and 2 inches thick of metal, for the reception of the tubes to be experimented upon. This cylinder, C, Plate I., was placed upon some balks of timber, in one of the locomotive pits, immediately under the shear legs A, A, for the convenience of lifting and replacing the heavy cover of the cylinder, which had to be removed at the close of each experiment. A small pipe, *a*, *a*, connected the force-pump, B, with the interior of the cylinder; and another, *b*, *b*, communicated with

the steam-pressure gauges at *c*, which exhibited the pressure in the cylinder during the experiment in lbs. per square inch: to ensure accuracy two gauges were employed, one of Schaeffer's and the other of Smith's construction, and the indications of these were checked by an accurate safety-valve, *d*. A small cock, *e*, served to let off the air contained in the cylinder when necessary.

Fig. 1.—*Vertical Section.*

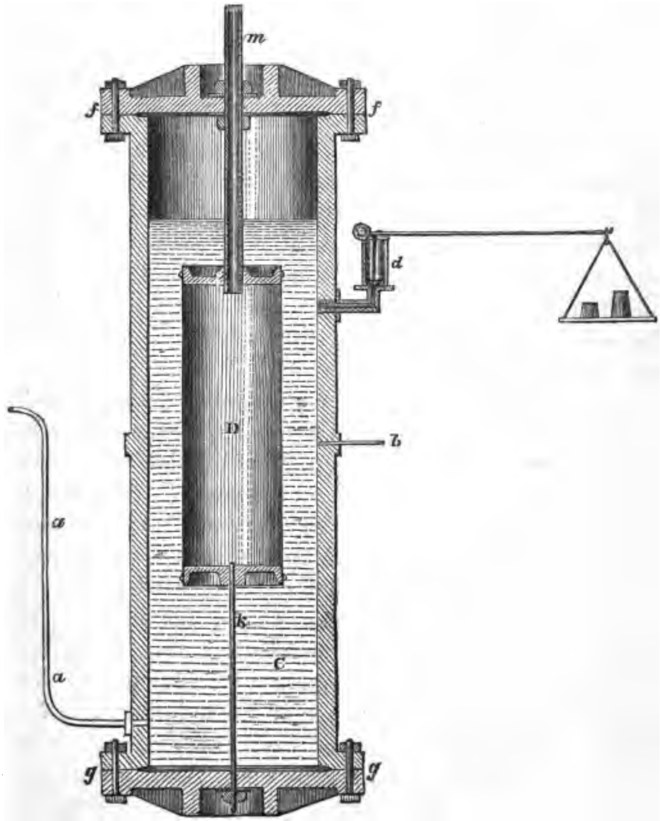


Fig. 1 is a section of the large cylinder. The top and bottom covers, *f* and *g*, were made of strength proportionate to that of the cylinder, to which they were secured by 1-inch bolts placed 3 inches apart. In the bottom cover, *g*, a hole was drilled, to receive the rod and screw-nut *k*, which supported the tube D to be experimented upon; and through the top passed a 2½-inch pipe, *m*, inserted in the cast-iron end of the tube D. On the end of this pipe was a large nut, which screwed down upon an indian-rubber washer on the cover of the cylinder, so as to close the opening round the pipe and make it water-tight. The object of this pipe was to allow the air from the interior of the tube D to escape during the collapse, and so to place it, as nearly as possible, under the same circumstances as the flue of a boiler.

The whole of the experiments were effected by means of the hydraulic pump, by which water was forced through the pipe *a a* into the cylinder C; thus driving the air in a highly compressed state to the upper part of the cylinder, whence, when a very high pressure was required, it was deemed advisable to let it escape by the cock *e*, and to effect rupture through the medium of water only. In both these cases a perfectly uniform pressure was ensured upon every part of the tube to be collapsed.

These preparations having been made, and the pressure-gauges carefully adjusted, the experiments proceeded as shown in the following Tables.

The first experiment was upon a tube 4 inches in diameter, and 1 foot 7 inches long between the cast-iron ends, to which it was riveted securely and brazed. It was composed, as in the other experiments, of a single thin plate, bent to the required form upon a mandril, and riveted, and also brazed to prevent leakage into the interior. This tube having been fixed to the cylinder covers in the manner described above, the pump was applied and a

gradually-increasing force given to its exterior surface, until its powers of resistance were overcome. During the experiments the precaution of allowing the air to escape at high pressures was found absolutely necessary, as the tubes generally collapsed with an explosion of the suddenly-compressed air in the tube D, fig. 1, accompanied by a loud report as it made its escape by the pipe *m*. These explosions give pretty correct indications of what takes place when the internal flues of boilers collapse.

It has long been a desideratum to determine some law by which the engineer could calculate the proportionate strength of the internal flues. Hitherto we have acted upon the principle that the cylindrical flues, as ordinarily constructed, were considerably stronger than the outer shell; but this opinion has in reality no foundation in experiment, excepting only uncertain deductions from occasional explosions and the failure of vessels under high pressures in circumstances of a very variable and doubtful character. There have been no definite rules to guide us hitherto in proportioning the diameter, length, and thickness of plates of the flues, so as to correspond with the strength of the boiler; and even in cases where explosions have taken place from collapse, we have, it is to be feared, too frequently mistaken the actual cause, in consequence of the débris covering the site, and the force which has torn to pieces the outer shell. The anomalous position in which these constructions are placed has greatly retarded the application of science to their improvement, and there appears, in fact, to be no rule known by which to attain uniformity of strength between those parts of a boiler exposed to an internal tensile, and those exposed to an external compressive force.

To supply this want, and to remedy certain anomalous results arising from defective forms of construction, it appeared desirable that these vessels should be subjected

to direct experiment, and the Laws of Resistance as far as possible ascertained, and the necessary formula deduced for the future guidance of the practical mechanic and engineer. These objects have, it is believed, been attained by the results developed in the experiments enumerated in the following Tables.

EXPERIMENTS.

Resistance of Tubes to Collapse.

In these experiments the tubes were composed of plates of uniform thickness, and of the form and size shown by the figures in the column of remarks. The form after collapse is also indicated by the woodcuts.

On consulting Table I., it appears that tubes of the same diameter and the same thickness of plates vary in strength when of different lengths. The tubes of 19 inches and those of 40 inches differ widely in their powers of resistance. Comparing the results of Experiments 1 and 2 with those of Experiments 3 and 4, we find that the latter, while of twice the length, bear less than half the pressure. Comparing these with Experiment 5, we find that tube E, 5 feet long or three times as long as A and B, exhibits only about one-third of their mean strength. Similarly, E, which is $\frac{5}{3}$ the length of D, bears only about $\frac{3}{5}$ the pressure.

Tube F, Experiment 6, may be considered as composed of three distinct tubes, each 1 foot 7 inches long. It was made with two perfectly rigid rings, soldered to the outside of the tube to keep it in form and prevent collapse at those points. The result of this alteration was to increase the strength of the tube threefold, as is evident on comparing it with tube E.

Table II. gives indications of the same law of resistance as the last. It will be observed that the tubes

TABLE I. *Resistance of 4-inch Tubes.*

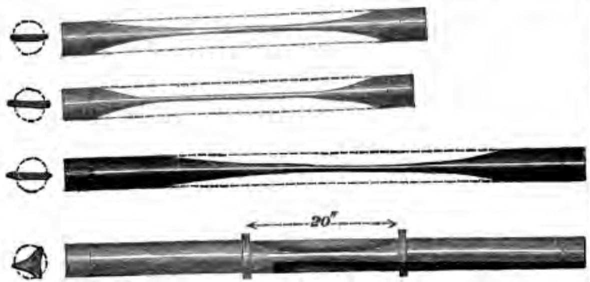
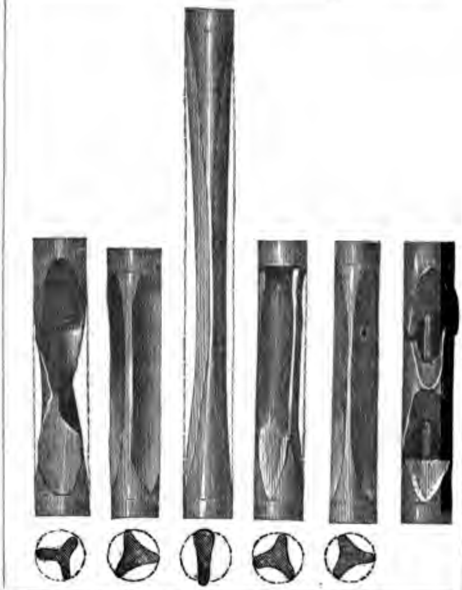
Mark.	No.	Diameter, inches.	Length, inches.	Thickness of plates. inch.	Pressure of collapse. lbs. per sq. in.	Remarks.
A.	1	4	19	·043	170	 N.B. The figures are drawn to a scale of $\frac{1}{2}$ in. = 1 ft. The cross-sections are taken through the line *a b*, where the collapse was greatest. The dotted lines show their form before they were subjected to experiment.
B.	2	4	19	·043	137	
C.	3	4	40	·043	65	
D.	4	4	38	·043	65	
E.	5	4	60	·043	43	
F.	6	4	60	·043	140	

TABLE II. *Resistance of 6-inch Tubes.*

Mark.	No.	Diameter, inches.	Length, inches.	Thickness, inches.	Pressure of collapse, lbs. per sq. in.	Remarks.
G.	7	6	30	·043	48*	
H.	8	6	29	·043	47*	
J.	9	6	59	·043	32	
K.	10	6	30	·043	52	
L.	11	6	30	·043	65	
M.	12	6	30	·043	85†	



* On removing the tubes G, H, it was found, that owing to the thinness of the metal, the cast-iron ends of both had been fractured, causing collapse, perhaps, before the outer shell had attained its maximum resistance.

† Tube M had an iron rod down its axis to prevent the ends approaching each other during collapse; a tin ring had also been left in by mistake, which accounts for the increased pressure required to produce collapse.

being screwed to the covers of the cylinder, were to some extent in a state of tension, owing to the necessity of having to screw up the air-tube tight in order to prevent leakage. This, with the weakness of the ends of the first two tubes, will account for the discrepancies in the Table. Making allowances on this ground, and taking the mean of the experiments, we arrive at the conclusion that the results approximate closely to the law that the strengths are inversely as the length; and this, it will be observed, is the result arrived at in the comparison of the 4-inch tubes.

Thus the mean strength of the tubes, 30 inches long, experiments G, H, K, L, is 53 lbs. per square inch. Now by the above inverse proportion, we may calculate from this the strength of a tube 59 inches long; thus,

$$59 : 30 :: 52 : x = 27,$$

the result being 32 in the above Table, Experiment 9, a difference of 5 lbs. only.

This law receives remarkable confirmation from Experiment 6 on tube F. This tube had, as already explained, two rigid cast-iron rings firmly soldered to it so as to divide its length into three equal parts. The result was to increase the strength threefold, or, in other words, to make it equal in strength to a tube of one-third the length.

The next series of tubes submitted to experiment were 8 inches in diameter, and of the same thickness as the preceding. In these experiments it will be seen that the same law in respect of the length prevails, and is perhaps more strikingly exemplified than in either of the preceding series. Perhaps from their larger size these tubes were less affected by defects of workmanship. Like the last, they had an outlet for the escape of the air, and collapsed with loud reports.

TABLE III. *Resistance of 8-inch Tubes.*

Mark.	No.	Diameter, inches.	Length, inches.	Thickness, inches.	Pressure of collapse, lbs. per sq. in.	Remarks.
N.	13	8	30	·043	39	
O.	14	8	39	·043	32	
P.	15	8	40	·043	31	

On comparing the above results, it will be found that there is a near approximation to the strengths being inversely as the lengths. Taking the strength of the first tube, 30 inches long, and calculating the force necessary to collapse the 39 and 40-inch tubes, we have, by calculation,

$$39 : 30 :: 39 : x = 30 \text{ and } 40 : 30 :: 39 : x = 29{\cdot}25\,;$$

the difference from the result in the Tables being 2 lbs. in the one case and $1\frac{3}{4}$ lb. in the other.

The following results on 10-inch tubes are also remarkably consistent with the above law.

Both tubes gave way, as in the preceding experiments, with a loud report. Comparing them, we have $50 : 30 :: 33 : x = 19{\cdot}8$; and by experiment (16) we have 19 lbs.

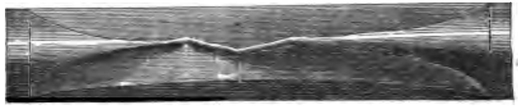
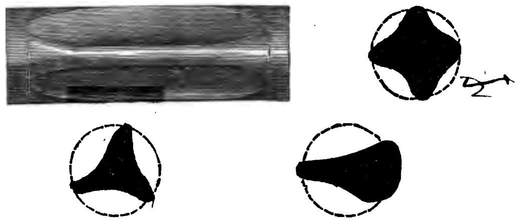
Equally strong evidence in confirmation of the law respecting the lengths, will be found in the Table of 12-inch tubes. The increase of diameter, without any change in the thickness of metal, does not affect it. On the contrary, this principle of resistance, in the case of tubes with unyielding ends and open for the escape of the contained air, holds true, uniformly, throughout the whole of the experiments on 4, 6, 8, 10, and 12-inch tubes, as nearly as could be expected when due allowance is made for variations in the rigidity and thickness of the plates, imperfections in the workmanship, and difference in the tension of the sides.

Taking Experiment 20 as correct, we have for the collapsing pressure of a similar tube, 5 feet long, $60 : 30 :: 22 : x = 11$, or 1·5 lb. less than Experiment 19. Similarly, $58\frac{1}{2} : 30 :: 22 : x = 11{\cdot}2$, or 0·2 lb. more than in Experiment 18. From these results we may reasonably conclude that the law affecting the strength of tubes is, other things being the same, that *the collapsing pressure varies inversely as the length.*

TABLE IV. *Resistance of 10-inch Tubes.*

Mark.	No.	Diameter, inches.	Length, inches.	Thickness, inch.	Pressure of collapse, lbs. per sq. in.	Remarks.
Q.	16	10	50	·043	19	
R.	17	10	30	·043	33	

TABLE V. *Resistance of* 12-*inch Tubes.*

Mark.	No.	Diameter, inches.	Length, inches.	Thickness, inches.	Pressure of collapse, lbs. per sq. in.	Remarks.
S.	18	12·2	58½	·043	11·0	
T.	19	12·0	60	·043	12·5	
V.	20	12·0	30	·043	22·0	

The tube S, when compared with the 6-inch tubes only one-half the length, required a pressure of less than one-fourth to cause collapse. This apparently low pressure, though at first sight anomalous, is confirmed by the result of Experiment 19. Similarly, comparing tubes C and D, Table I., with tubes O and P, Table III., we have,

	Length.	Diameter.	Pressure.
C and D . .	39 . .	4 . .	65
O and P . .	39 . .	8 . .	31·5;

that is, whilst the diameters are to one another as 1 : 2, the pressures of collapse are as 65 : 31·5, or as 2 : 1 very nearly. These comparisons, which might be continued, evidently point to a law affecting the diameters similar to that of the lengths.

In order to ascertain the different powers of resistance of tubes composed of thick plates and of different diameters, a strong tube only 9 inches in diameter, and formed of a plate $\frac{1}{4}$-inch thick, was constructed, to match and compare with another tube, also of $\frac{1}{4}$-inch plate, and 18$\frac{3}{4}$-inches in diameter. The 9-inch tube was, however, found to be too strong for the retaining powers of the cylinder, which it would not have been safe to have trusted above 500 lbs. per square inch. Finding the strength of the small tube too great for the containing vessel, two new tubes were made, one with a lap-joint as at A in the annexed sketch, and another with a butt-joint as at B. These tubes were made of plates $\frac{1}{8}$th of an inch thick, the object of the difference being two-fold;—*first*, to ascertain to what extent the strength of the tube was reduced by the lap-joint; and *secondly*, to compare with the tube 18$\frac{3}{4}$ inches in diameter,

Fig. 2.

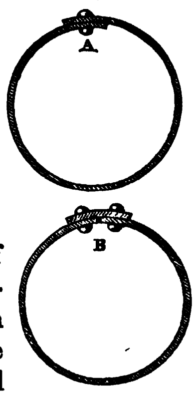
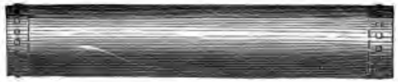
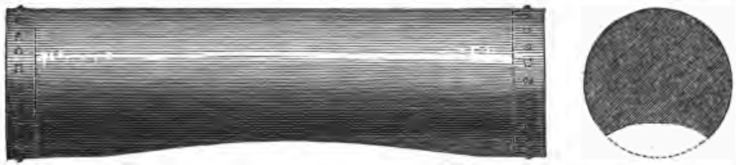


Table VI. *Resistance of Tubes with lap- and butt-joints.*

Mark.	No.	Diameter, inches.	Length, inches.	Thickness, inch.	Pressure of collapse, lbs. per sq. in.	Remarks.
W.	21	9	37	·25	(450)	Uncollapsed. 
X.	22	$18\frac{3}{4}$	61	·25	420	
Y.	23	9	37	·14	262	Lap-joint. 
Z.	24	9	37	·14	378	Butt-joint. 

and double the thickness of plates. In the construction of boilers the lap-joint is almost invariably in use; and it must at once appear obvious that any such departure from the true circle in cylindrical tubes must impair their powers of resistance to external pressure.

The tube Y, Experiment 23, was made with a lap-joint, which caused it to deviate from a true circle in form, to the extent of nearly a quarter of an inch, the double thickness of the plates. In the tube Z, the cylindrical form was better maintained by the butt-joint, and this difference, apparently so small, had a serious effect upon the resisting powers of the tube. According to the results in the Table, there was a loss of more than one-third of the strength in the tube with the lap-joint, the ratio being 69·3 : 100, or 7 : 10 nearly. These facts are conclusive in showing the necessity of adhering in these constructions to the true cylindrical form.

The foregoing experiments were instituted for the purpose of ascertaining the resistance of tubes to collapse, when the ends were securely fixed to unyielding discs (as is the case with the flues of a boiler), and rigidly kept apart to prevent their approaching one another. In this position, the tubes, when submitted to severe collapsing pressures, were to some extent in a state of tension, and in some few cases, when collapse took place, the sides were torn from the cast-iron discs.

The results obtained from tubes of this construction have already been recorded, but we have yet to ascertain to what extent tubes of the same size and form follow the same laws in their resistance to external pressure when their ends are left free to approach each other. To solve this question two tubes were made, similar to those previously experimented upon, of 8 inches diameter and 60 and 30 inches in length. In these tubes there was no rigid bar down the centre, nor were they attached to the

TABLE VII. *Resistance of 8-inch Tubes.*

Mark.	No.	Diameter. inches.	Length. inches.	Thickness. inch.	Pressure of collapse. lbs. per sq. inch.	Remarks.
AA.	25	8	60	·043	22	
BB.	26	8	30	·043	36	

TABLE VIII. *Resistance of 4-inch Tubes.*

Mark.	No.	Diameter. inches.	Length. inches.	Thickness. inch.	Pressure of collapse. lbs. per sq. inch.	Remarks.
CC.	27	4	60	·043	47	
DD.	28	4	30	·043	(195)	
EE.	29	4	30	·043	93	
FF.	30	4	15	·043	147	

cylinder covers; they were simply placed in the cylinder, and water pumped in, in the usual manner, until they collapsed as given in Table VII.:—

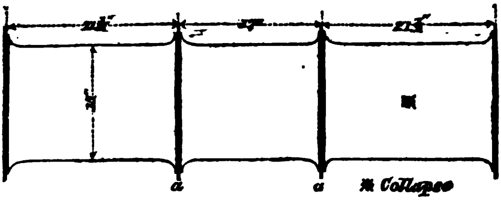
In the above experiments the tubes do not appear to follow precisely the law of "inversely as the length." Had they done so, the tube BB should not have yielded with a less pressure than 44 lbs. on the square inch. It is, however, impossible to manufacture these tubes truly cylindrical, and hence it follows that slight variations may very materially affect the ultimate strength of the tube.

From three experiments on 4-inch tubes, we derive data more in accordance with the law, as will be seen in Table VIII.

In the above experiments, the second on tube DD is lost, in consequence of the ends being fractured and the water obtaining admission, so as to cause a counteracting pressure in the interior. Experiment 29 agrees closely with the law when compared with 27, its strength being correctly double that of the latter. The 15-inch, although not four times the strength of the 60-inch, exhibits high resisting powers. It is probably difficult to reconcile these discrepancies; but we have in these experiments sufficient data to show that these tubes also follow, in their resistance to collapse, some function of the length; and it is important to observe, that we cannot in practice introduce long tubes into constructions exposed to external pressure, without making very considerable allowance for their loss of strength.

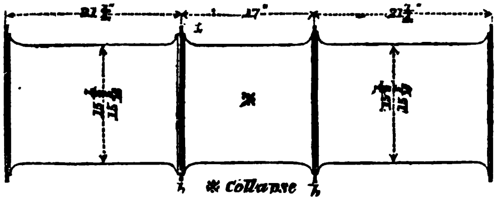
In the earlier experiments the tubes were made of thin wrought-iron plates; but conceiving that it would be of interest to examine how far the laws, which were found to prevail with them, applied also to tubes of other materials, three tubes were made of the following dimensions:—

GG. Iron flue, 15 inches in diameter:—



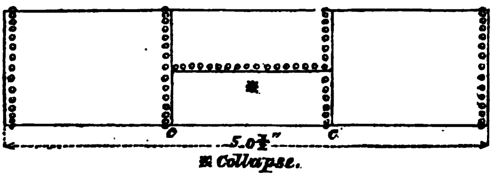
Plates ·125 inch thick.
Web (*a a*) ·25 inch thick.
Rivets $\frac{1}{4}$ inch, at $1\frac{1}{4}$ inch apart.

HH. Steel flue, diameters $15\frac{3}{16}$ and $15\frac{5}{8}$ inches:—



Plates ·125 inch thick.
Web (*b b*) ·25 inch thick.
Rivets $\frac{1}{4}$ inch, at $1\frac{1}{4}$ inch apart.

JJ. Iron flue, with overlap joints; diameters $14\frac{1}{2}$ and $14\frac{11}{16}$ inches:—



Plates ·125 inch thick.
Ends ·25 inch thick.
Length 5 feet.
Rivets $\frac{1}{4}$ inch, at $1\frac{1}{4}$ inch apart.

TABLE IX. *Resistance of Steel and Iron Flues.*

Mark.	No.	Diameters. inches.	Length. inches.	Thickness. inch.	Pressure of collapse. lbs. per sq. in.	Remarks.
GG.	31	15	21	·125	150	Each had an internal longitudinal stay between the ends.
HH.	32	$15\frac{3}{16} \times 15\frac{5}{8}$	17	·125	220	
JJ.	33	$14\frac{1}{2} \times 14\frac{11}{16}$	60	·125	125	

The experiments on these tubes do not at first sight appear to yield very satisfactory results. The first, GG, gave way with a pressure of 150 lbs. on the square inch, when it began to leak so much as to cause its removal from the vessel, to replace some of the rivets which were imperfect. After the necessary repairs, it was again subjected to experiment, when it gave way with a force of 146 lbs., showing how much it had been injured by the previous pressure. On comparing it with the mean results of all the other experiments, we find that it should have borne about 300 lbs.: it evidently failed at the rivets, and cannot be relied upon.

The next experimented upon was a steel tube, of the same form and with similar rigid divisions to those of the iron one. This sustained 220 lbs. on the square inch, when it bulged in or collapsed in the middle division.

The last was a plain tube of similar plates of iron, $14\frac{5}{8}$ inches in diameter, but without ribs. This collapsed with a pressure of 125 lbs. on the square inch; and this agrees nearly with the preceding experiments, as will be seen.

Comparing Experiments 32 and 33, it would appear that the steel tube is not stronger than the iron; but we are not warranted in drawing general conclusions from a single experiment.

The next experiments were of a different character, upon tubes of an elliptical form. Table X. gives the results.

The two experiments on cylindrical tubes are appended for comparison.

On comparing the elliptical tube B*b* with the cylindrical tube X, which are of the same length and thickness of plates, and only about half a square inch different in sectional area, we have for the collapsing pressure of the former 127·5 lbs., and for that of the latter 420 lbs., where it will be observed there is a loss of about $\frac{4}{7}$ths of the strength, in consequence solely of the flattening of the tube B*b*, or in other words, a cylindrical tube will support nearly three times the pressure which would collapse an elliptical tube of the same weight when proportioned like tube B*b*. A similar deficiency is observable in tube A*a*, when compared with tube T. The change of form, from the cylinder to the ellipse, where the diameter was reduced to $1\frac{1}{2}$ inch in one direction and extended as much in another, reduced the bearing powers one-half. The comparative results obtained from the experiments on the thick tube are different from those on the thin one, the loss being much greater in the former than in the latter case, although the ratio of the diameters is about the same. Allowance must, however, be made for inaccuracies of construction, though we might reasonably have expected a nearer approximation in the ratios of the deficiency of strength. From these facts, however, it is obvious that in every construction, where tubes have to sustain a uniform external pressure, the cylindrical is the only form to be relied upon, and any departure from it is attended with danger.

TABLE X. *Resistance of Elliptical Tubes.*

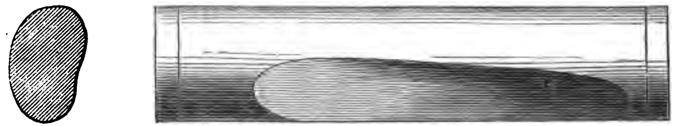
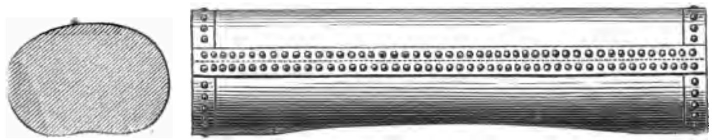
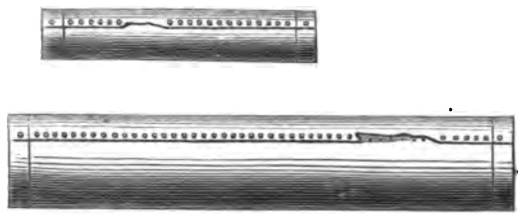
Mark.	No.	Diameter. inches.	Length. inches.	Thickness. inch.	Pressure of collapse. lbs. per sq. inch.	Remarks.
A*a*.	34	$14 \times 10\frac{1}{4}$	60	·043	6·5	
B*b*.	35	$20\frac{3}{4} \times 15\frac{1}{2}$	61	·250	127·5	
X.	22	$18\frac{3}{4}$	61	·250	420·0	Cylindrical.
T.	19	12	60	·043	12·5	Cylindrical.

Table XI.—*Resistance of Tubes to Internal Pressure.*

Mark.	No.	Diameter. inches.	Length. inches.	Thickness. inches.	Pressure of rupture. lbs. per sq. inch.	Remarks.
C*c*.	36	6	12	·043	475	
D*d*.	37	6	24	·043	235	
E*e*.	38	6	30	·043	230	
F*f*.	39	6	48	·043	375	
G*g*.	40	12·13	60	·043	110	



Resistance of Tubes to Internal Pressure.

During the investigation on the comparative resisting powers of tubes to collapse, a question arose as to the relative powers of cylindrical tubes to resist an internal force acting uniformly over their surface. It has already been demonstrated that the resistance of cylindrical vessels to internal pressure varies inversely as the diameters, but what effect the length may have upon the strength has yet to be determined. We have already seen that a cylindrical tube, when subjected to external pressure, loses one-half its strength when the length is doubled, and so on in other cases; hence arose the inquiry, what effect, if any, will an increase of length have upon a tube exposed to *internal* pressure? To solve this problem, three tubes of precisely the same diameter and thickness of plates, but of different lengths, were prepared and submitted to experiment as seen in Table XI.

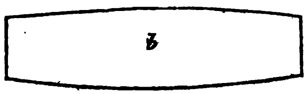
Considerable discrepancies occur in the experiments on internal pressure, as in each case the tube gave way at the riveted joint. Every precaution was taken, by carefully brazing them, to render them as nearly uniform in strength as possible. The weakness of these joints was, however, very apparent, and the results are in accordance with those arrived at several years previously, when it was found that the strengths of riveted plates were as the numbers—

100, for the solid plate;
70, for the double-riveted joint;
56, for the single-riveted joint.

This constant failure at the joints renders the experiments on internal pressure very unsatisfactory, as they do not exhibit the ultimate strength of the plate, but only the strength of the joint; and as boilers invariably present

joints, these facts are probably of some significance when applied to them. On a careful examination of the fractures, that of the tube F*f* appeared the most perfect. E*e* was not so well soldered, and burst by tearing off the rivet-heads, and D*d* was torn partly through the plates and partly through the rivets; the plate of which this tube was composed was, however, exceedingly brittle, and broke like cast-iron. Tube G*g* was ruptured in the same way and in the same direction as the others; the rivets were torn through the plates, and the soldering (not very sound) was ripped up for 10 inches along the joint: this tube, as also the others, would have borne a greater pressure had the joints been more perfect and of sounder workmanship.

Comparing the tube C*c*, 1 foot long, with the tube F*f*, 4 feet long, and assuming the joints to be equally perfect in each, it would appear that there is a slight loss of strength when the length is increased; and this again suggests the question, do the rigid ends in short tubes increase the strength of the unsupported portion in proportion to the length of the tube? For example, let us take two tubes of any given diameter, the one 10 feet and the other 20 feet long; it would appear, *primâ facie*, that



it was much easier to force the long tube into the form of a barrel, as at *a*, than it would be to produce the same

form in the shorter tube, as at *b*; in an elastic material, such as an indian-rubber tube, the extension would certainly take place at the centre, where the particles possess diminished resistance, arising from their respective distances from the ends or points of support.

To ascertain how far this view is correct, two leaden pipes were prepared of 3 inches diameter, and of the lengths of 1 foot 2½ inches, and 2 feet 7 inches respectively, and these were submitted to the experimental tests in Table XII., :—

The tube H*h* ruptured at the thin part of the metal, the water bursting through a narrow slit; J*j* ruptured similarly; and on measuring the expanded circumferences at the broadest part, it was found that the metal of the former had elongated 1¼ inch, and that of the latter 1½ inch.

These experiments seem to show pretty conclusively, that the length has very slight influence on the resisting powers of tubes of *wrought iron* to internal pressure. Beyond the limit of one or two feet in length, it appears to affect the strength so slightly, that it may be almost entirely disregarded in practice.

GENERALISATION OF THE RESULTS OF THE EXPERIMENTS.

In the reduction of the experiments, I have, as on former occasions, been ably assisted by my friend Mr. Tate, whose sound philosophical views and high mathematical attainments are, from his numerous publications, so well known to the public. To that gentleman I am indebted for many services, and among others for an elaborate inquiry into the specific gravity and properties of steam, which I hope will be shortly forthcoming as a new addition to our knowledge, and that more particularly in

TABLE XII.—*Resistance of Lead Tubes to Internal Pressure.*

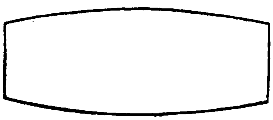
Mark.	No.	Diameter. inches.	Length. inches.	Thickness. inches.	Pressure of rupture. lbs. per sq. inch.	Remarks.
H*h*.	41	3	$14\frac{1}{2}$	·25	374	At 225 lbs. pressure for H*h*, and 325 lbs. for J*j*, the ends were blown out. 
J*j*.	42	3	31	·25	364	After having been taken out and the ends replaced, they burst, as in the Table. 

its application to the wants and necessities of the present high state of civilisation.

On this question I am personally gratified to find the subject in such able hands, and aided by the industry, care and perseverance of my own assistant, Mr. W. C. Unwin, I entertain hopes of rendering the researches now in progress of such a character as fully to justify the application of the word *useful*, which of all others is probably the best calculated to express the true value of these investigations.

Formulæ of Strength relative to Cylindrical Tubes.

The strain which the material of a cylindrical vessel undergoes, when a uniformly-distributed external pressure is applied to it, is very different from the strain produced when the pressure acts internally. In the latter case the material is equally extended throughout all its parts, and its cylindrical form is preserved at all stages of the pressure, with the exception of a small portion closely bordering upon the inflexible plates closing the extremities. The tube under a high internal pressure will assume the form represented in the annexed diagram, and the relation of the force of rupture to that of resistance will be approximately expressed by



$$P=\frac{2E \times k}{D}, \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where P represents the pressure requisite to produce rupture, E the ultimate resistance of the material to extension, D the diameter of the tube, and k its thickness; whereas in the former case, the material, being compressed, becomes crumpled in longitudinal lines near the middle; the tube loses its original cylindrical shape at and near to that

part, whilst the portions towards the extremities being supported by the inflexible end plates, retain, or nearly retain, their original form; so that, in fact, the material virtually resisting compression is the comparatively small portion at and near the middle, and which, to a certain extent, is independent of the length of the tube, whilst the pressure producing the compression is always approximately proportional to the longitudinal section. Now let us assume for these tubes,—

P' = the external pressure of the fluid in lbs. to produce rupture or collapse;
P = this pressure per square inch;
R = the resistance of the material to compression or to crumpling;
L = the length of the tube in feet;
D = the diameter of the tube in inches;
k = the thickness of the plates in inches;
p = the pressure P reduced to unity of length and diameter, or $= PLD$;
C, a, constants to be determined from the data supplied by the experiments.

Since P', the total pressure on the tube, varies directly as the longitudinal section, that is, as the product of the length by the diameter, we have

$$P' = C'.P.L.D.$$

Now it has been determined by experiment, that the resistance of thin iron plates to a force tending to crush them, or rather to a force tending to crumple them, varies directly as a certain power of their thickness, the number indicating the power lying between 2 and 3; hence we assume,

$$R = C.''k^{a};$$

but when rupture takes place, $P' = R$, and

$$C'.P.L.D = C''.k^{a},$$

$$\therefore \quad P = \frac{Ck^{a}}{LD} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

For tubes of the same thickness, we readily derive from this equality,

$$P.L.D. = P_{,}.L_{,}.D_{,}; \quad . \quad . \quad . \quad . \quad . \quad (3)$$

that is, the continued product of the pressure, the length and the diameter is constant; or in other words, for tubes having the same thickness, the pressures of collapse reduced to unity of length and diameter (p) are equal to one another.

To determine the values of the constants a and C in (2), we have

$$\frac{PLD}{P_{,}L_{,}D_{,}} = \left(\frac{k}{k_{,}}\right)^{a}.$$

But in order to embrace a range of experiments by taking the mean of their results, we have, putting p for the value of P, when the tube is reduced to unity of length and to unity of diameter,

$$\frac{p}{p_{,}} = \left(\frac{k}{k_{,}}\right)^{a},$$

$$\therefore \quad a = \frac{\log p - \log p_{,}}{\log k - \log k_{,}}; \quad . \quad . \quad . \quad . \quad (4)$$

and similarly, we find

$$C = \frac{p}{k^{a}}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

A glance at the results of the experiments recorded in Tables I. II. III. IV. V., where the thickness of the plates composing the tubes is the same, is sufficient to show,—1st, that the strength of the tubes varies nearly

inversely as their lengths; 2ndly, that the strength also varies nearly inversely as the diameters. The following reduction of these experiments will not only render these laws apparent, but will also show that in tubes of the same thickness the strength varies inversely as the product of their lengths by their diameters, or what amounts to the same thing, that PLD ($=p$) is nearly a constant quantity.

Reduction of the Results of the Experiments on the Collapse of Sheet-iron Tubes ·043 *inch thick, to unity of length and diameter.*

Experiments 1, 2 and 6, were performed on tubes of the same length and diameter, and also Experiments 7, 10 and 11; hence we have for the mean values of P,—

Mean value of P from Experiments, 1, 2 and 6

$$=\frac{170+137+140}{3}=149.$$

Mean value of P from Experiments 7, 10 and 11

$$=\frac{48+52+65}{3}=55.$$

4-inch Tubes.

No. of Experiment.	D. Diameter in Inches.	L. Length in Feet.	P. Pressure of Collapse in lbs.	P. L. Pressure reduced to Unity of L.	P. D. Pressure reduced to Unity of D.	p. Pressure reduced to Unity of L and D.
1, 2, 6	4	$1\frac{7}{12}$	149	232·5	596	930·0
3	4	$3\frac{1}{3}$	65	216·6	260	866·4
4	4	$3\frac{1}{6}$	65	205·8	260	823·2
5	4	5	43	215·8	172	860·0
27	4	5	47	235·0	188	940·0
29	4	$2\frac{1}{2}$	93	232·5	372	930·0

6) 5349·6

Mean value of p . . 891·6

D

The approximation of the numbers to one another in columns 5 and 7 shows how very nearly the strength varies inversely as the lengths. This observation applies with equal exactness to all the reductions which follow.

6-inch Tubes.

No. of Experiment.	D.	L.	P.	P. L.	P. D.	*p*.
7, 10, 11	6	$2\frac{1}{2}$	55	137·5	330	825
9	6	$4\frac{11}{12}$	32	157·3	192	944

2) 1769

Mean value of *p* . . 884·5

8-inch Tubes.

No. of Experiment.	D.	L.	P.	P. L.	P. D.	*p*.
13	8	$2\frac{1}{2}$	39	97·5	312	780·0
14	8	$3\frac{1}{4}$	32	104·0	256	832·0
15	8	$3\frac{1}{3}$	31	103·3	248	826·4

3) 2438·4

Mean value of *p* . . 812·8

10-inch Tubes.

No. of Experiment.	D.	L.	P.	P. L.	P. D.	*p*.
16	10	$4\frac{1}{6}$	19	79·1	190	791
17	10	$2\frac{1}{2}$	36	90·0	360	900

2) 1691

Mean value of *p* . . 845·5

A comparison of the numbers in the sixth columns of the above Tables with the numbers given by the experiments on tubes of the same length, clearly shows that the strength varies very nearly in the inverse ratio of the diameters; and, moreover, since the mean values of *p* for the different sets of tubes nearly coincide with one another,

we infer that the strength varies inversely as the product of the length by the diameter, or that $p = \text{PLD} =$ a constant.

12-*inch Tubes.*

No. of Experiment.	D.	L.	P.	P. L.	P. D.	p.
18	12·2	$4\frac{21}{24}$	11·0	53·6	123·2	654
19	12	5	12·5	62·5	150·0	750
20	12	$2\frac{1}{2}$	22·0	55·0	264·0	660

3) 2064

Mean value of p . . . 688

Here the mean value of p is somewhat below the value determined from the other tubes. This discrepancy is no doubt owing to the difficulty there is in maintaining such thin tubes of large diameter exactly in the cylindrical form. This circumstance seems to suggest that a small correction, depending on the ratio of the diameter of the tube to its thickness, may be requisite to render formula (2.) mathematically exact. This correction will assume the form of $- \text{E} \times \frac{\text{D}}{k}$, where the constant E remains to be determined from the data of the experiments.

Mean value of p *derived from the foregoing results.*

$$p = \tfrac{1}{5}\{891{\cdot}6 + 884{\cdot}5 + 812{\cdot}8 + 845{\cdot}5 + 688\} = 824.$$

Reduction of the Results of Experiments 22, 24, 33 *on the Collapse of Sheet-iron tubes to unity of length and diameter.*

No. of Experiment.	D.	L.	k Thickness.	P.	p.
22	$18\frac{3}{4}$	$5\frac{1}{12}$	·25	420	40,030
24	9	$3\frac{1}{12}$	·14	378	10,495
33	$14\frac{5}{8}$	5	·125	125	9,140

To find the Value of the Constants α and C in the General Formula.

In equality (4), taking $p=40{,}030$, $k=\cdot 25$, $p_{,}=820$, $k_{,}=\cdot 043$; we get

$$\alpha=\frac{\log 40{,}030-\log 820}{\log \cdot 25-\log \cdot 043}=2\cdot 23.$$

Similarly, taking $p=40{,}030$, $k=\cdot 25$, $p_{,}=9140$, and $k_{,}=\cdot 125$; we get

$$\alpha=\frac{\log 40{,}030-\log 9140}{\log \cdot 25-\log \cdot 125}=2\cdot 14;$$

and taking $p=10{,}495$, $k=\cdot 14$, $p_{,}=820$, $k_{,}=\cdot 043$; we get

$$\alpha=\frac{\log 10{,}495-\log 820}{\log \cdot 14-\log \cdot 043}=2\cdot 16;$$

and taking the mean of these values, we get $\alpha=2\cdot 19$.

For the value of the constant C, we have from (5),

$$C=\frac{p}{k^{\alpha}}=\frac{820}{\cdot 043^{2\cdot 19}}=806{,}300.$$

Substituting these values in (2.), we get

$$P=806{,}300\times\frac{k^{2\cdot 19}}{LD}, \quad . \quad . \quad . \quad . \quad (6)$$

which is the general formula for calculating the strength of wrought-iron tubes subjected to external pressure*, within the limits indicated by the experiments; that is, provided their length is not less than 1·5 foot, and not

* By taking 2 instead of 2·19 for the index of k, this formula becomes

$$P=806{,}300\times\frac{k^{2}}{LD}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (a)$$

whence the value of P, the collapsing pressure may be readily calculated by ordinary arithmetic.

For thick tubes of considerable diameter and length, this formula may be regarded as sufficiently exact for practical purposes.

For example, let $k=\frac{1}{2}$ inch, $L=10$ feet, $D=36$ inches; then

$$P=806{,}300\times\frac{(\frac{1}{2})^{2}}{10\times 36}=560 \text{ lbs.}$$

By formula (6), $\div$ $P=1\cdot 5265+2\cdot 19\log 50-\log 360=502$ lbs.

It will be observed that these results do not differ widely from each other.

greater probably than 10 feet. For greater lengths the formula gives the collapsing pressure somewhat too low, although the experiments on flues 30 feet long, to be adverted to hereafter, show that up to that point the variations from the theoretical collapsing pressure does not exceed one-fourth.

In order to facilitate calculation, formula (6) may be written,

$$\log P = 1{\cdot}5265 + 2{\cdot}19 \log 100\,k - \log (\mathrm{LD});$$

and when $k = {\cdot}043$, by an obvious transformation, we have

$$P = \frac{820}{\mathrm{L.D}}.$$

The following Table will show how nearly formula (6) represents the results of the experiments on the different classes of tubes.

No. of Experiment.	D. Diameter. Inches.	L. Length. Feet.	k. Thickness. Inches.	P. By Experiment in lbs.	P. By Formula (6.	Proportional Error by Formula.
2	4	$1\frac{7}{12}$	·043	137	130	$-\frac{1}{19}$
5	4	5	·043	43	41	$-\frac{1}{22}$
7, 10, 11	6	$2\frac{1}{2}$	·043	55	54·7	$-\frac{1}{200}$
14	8	$3\frac{1}{4}$	·043	32	31·6	$-\frac{1}{80}$
16	10	$4\frac{1}{6}$	·043	19	19·7	$+\frac{1}{30}$
19	12	5	·043	12·5	13·6	$+\frac{1}{12}$
20	$18\frac{3}{4}$	$5\frac{1}{12}$	·250	420	407	$-\frac{1}{32}$
26	9	$3\frac{1}{12}$	·140	378	392	$+\frac{1}{27}$
33	$14\frac{5}{8}$	5	·125	125	116	$-\frac{1}{15}$

So far as regards practical purposes, this formula appears to possess every desirable precision. As already anticipated, the results derived from the thin 12-inch tubes present the greatest deviation. The value of P, derived from the following formula, gives a still closer approximation to the results of the experiments, viz.—

$$P = 806{,}300 \times \frac{k^{2\cdot19}}{\mathrm{L.D}} - {\cdot}002 \times \frac{D}{k}.$$

It is highly desirable that we should verify the law $P.L.D = P_{\prime}.L_{\prime}.D_{\prime}$, as applied to thick tubes. Now, we know the value of α independently of these experiments, for its value, as determined above, closely approximates to the value derived from the experiments on the compression of sheet-iron plates. Let us, therefore, reduce the collapsing pressure of these plates to unity of thickness, with the view of ascertaining the law of variation of pressure as regards length and diameter.

Let P be the pressure of collapse of a tube k inches thick, and P′ the pressure when the tube is ·1 inch thick; then

$$\frac{P'}{P} = \left(\frac{\cdot 1}{k}\right)^{\alpha},$$

$$\therefore \quad P' = P \times \left(\frac{1}{10k}\right)^{\alpha} = \frac{P}{(10k)^{\alpha}},$$

and

$$\log P' = \log P - 2{\cdot}19 \log (10k).$$

Reducing the values of P by this formula, we derive the following results:—

No. of Experiment.	D. Diameter.	L. Length.	k. Thickness	P. Pressure.	P′, or Value of P reduced to Unity of Thickness, viz. 1.	Value of P′. L. D.
5	4	5	·043	43	273	5400
22	$18\frac{3}{4}$	$5\frac{1}{12}$	·250	420	57	5400
24	9	$3\frac{1}{12}$	·140	378	190	5300
33	$14\frac{5}{8}$	5	·125	125	76	5600

The remarkable approximation of the numbers in the last column to one another, distinctly establishes the law $(P.L.D = P_{\prime}.L_{\prime}.D_{\prime})$ in relation to tubes composed of thick plates.

Deduction from the Results of the Experiments on the Collapse of Elliptical Tubes.

By comparing the result of Experiment (34) on the

elliptical tube with the result of the experiments on the cylindrical tubes, we find that the general formula (6) will apply approximately to elliptical tubes, by substituting for D in that formula the diameter of the circle of curvature touching the extremity of the minor axis. Thus we have.

Diameter of the circle of curvature $=\frac{2a^2}{b}=\frac{2\times 7^2}{5}=20$ nearly.

Now the pressure on this elliptical tube was 6·5 lbs., which reduced to unity of length and diameter, gives 650 lbs., which result nearly agrees with 688 lbs., the mean pressure of the 12-inch tubes also reduced to unity of length and diameter.

Although this deduction is based on merely one experimental result, yet it appears to be confirmed by the following proposition derived from mathematical analysis.

The pressure P per square inch, requisite to flatten equal angular portions of a tube of variable curvature, varies inversely as the diameters of curvature.

Hence it will be observed how very much the strength of a tube subjected to external pressure is deteriorated by a deviation from the cylindrical form.

Strength of Cylindrical Tubes subjected to Internal Pressure.

Taking the mean of the results of Experiments 36 and 39 on iron tubes, we have from formula

$$E=\frac{425\times 6}{2\times \cdot 043}=30{,}000 \text{ nearly.}$$

Hence we find

$$P=\frac{60{,}000k}{D}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (7)$$

which gives the formula of strength of thin sheet-iron tubes subjected to internal pressure.

Now the tenacity of boiler plates has been found to be 23 tons, or 51,520 lbs. per square inch; hence it appears that a considerable reduction of tenacity must be made for the riveting of the plates. The ratio of reduction is in this case $\frac{3}{5}$.

One remarkable fact distinctly established by these experiments, is the comparative weakness of tubes subjected to external pressure. If p be put for the internal pressure per square inch at which a tube is ruptured, then for tubes of the same thickness and diameter, we find from (6) and (7) the following relation of strength:—

$$\frac{p}{P}=\frac{1}{13\cdot44}\times\frac{L}{k^{1\cdot19}}$$

If $L=2\frac{1}{2}$ and $k=\cdot043$ then $\frac{p}{P}=7\cdot77$; that is to say, in this case the tube subjected to internal pressure will have about $7\frac{1}{2}$ times the strength of a similar tube subjected to external pressure. When

$$p=P,$$

we find

$$L=13\cdot44k^{1\cdot19}.$$

If $k=\cdot25$, then we find $L=3\frac{3}{4}$ feet nearly; that is, a tube of this length and thickness will be equally strong whether subjected to external or internal pressure.

Taking the mean of Experiments 41 and 42 on the lead pipes, we have from formula (1),—

$$E=\frac{370\times3}{2\times\cdot25}=2220,$$

which gives us the tenacity of lead per square inch.

Hence we find

$$P=\frac{4440k}{D}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

which gives the formula of strength of lead tubes subjected to an internal pressure.

Practical Application to Construction of the Results of the Experiments.

Throughout the whole of the experiments enumerated in the preceding pages, it has been proved that the resistance to collapse from a uniform external pressure, in cylindrical tubes, varies in the inverse ratio of the lengths. This law has been tested to lengths not exceeding fifteen diameters of the tube; but the point at which it ceases to hold true is as yet undetermined, and could only be ascertained by a new and laborious series of experiments on tubes of considerably greater length, in which the strength of the material modifies the above law of resistance to collapse. Such experiments are, doubtless, very desirable; but the vessels necessary for the purpose would be most expensive, and the results already obtained appear to supply all the data necessary for calculating the strengths and proportioning the material in all ordinary cases.

If we take a boiler of the ordinary construction, 30 feet long and 7 feet in diameter, with one or more flues 3 feet or 3 feet 6 inches in diameter, we find that the cylindrical external shell is from three to four times stronger in its powers of resistance to the force tending to burst it, than the flues are to resist the same force tending to collapse them. This being the case in boilers of ordinary construction, it is not surprising that so many fatal accidents should have occurred from the collapse of the internal flues, followed immediately by the explosion and rupture of the outer shell. To remedy these evils, and to place the security of vessels so important to the community upon a more certain basis, it is essential that every part should be of *uniform strength* to resist the forces brought to bear upon it. The equalisation of the powers of resistance is the more important, as the increased

strength of the outer shell is absolutely of no value, so long as the internal flues remain, as at present, liable to be destroyed by collapse, at a pressure of only one-third of that required to burst the envelope which surrounds them.

The following Table, deduced from my own experiments, exhibits the safe working pressure, and the bursting pressure of boilers of different diameters, calculated for an external shell of a thickness of $\frac{3}{8}$ths of an inch.

Diameter of Boiler.		Working Pressure.	Bursting Pressure.
ft.	in.	lbs.	lbs.
3	0	118	708¼
3	6	101	607
4	0	88½	531
4	6	78¾	472
5	0	70¾	425
5	6	64¾	386¼
6	0	59	354
6	6	54¼	326¾
7	0	50½	303½
7	6	47	283¼
8	0	44	265¾
8	6	41½	250

Taking from the above Table the strength of a boiler 7 feet in diameter, we find its bursting pressure to be 303 lbs. per square inch. For such a boiler the flues would be ordinarily 3 feet in diameter, and of the same thickness of plates as the shell; and by the formula, $\log P = 1{\cdot}5265 + 2{\cdot}19 \log 100k - \log(L.D.)$, we obtain for their collapsing pressure, 87 lbs. per square inch. As, however, the formula does not apply with strictness to tubes of such length, the actual collapsing pressure will be somewhat greater than this. The immense excess of strength in the outer shell is, however, sufficiently apparent; the extra thickness of boiler plate which causes it being so much material

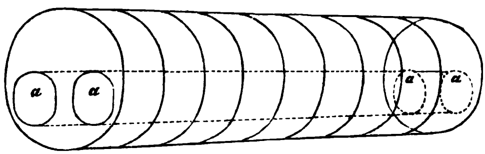
thrown away, adding nothing to the strength whilst the flues remain in so dangerously weak a condition.

To meet this disparity of strength, the experiments indicate the necessity of *shorter* flues, and one of them shows how this may be obtained, practically and efficiently, without interfering with the present construction of boilers. In Experiment 6, Table I., the tube F was divided into three parts by two rigid rings soldered upon its exterior, and its powers of resistance were thus increased in the ratio of three to one; *virtually*, the length was reduced in this ratio, and the strength was *actually* increased from 43 to 140 lbs. per square inch.

It is proposed to apply a similar construction to the flues of boilers, to equalise their powers of resistance with those of the outer shell, on the supposition that the law of decrease of strength holds true, within no great limits of error, for tubes of much greater length than in the preceding experiments. That this conclusion is not empirical, will be seen by the following experiments upon boilers of full size, where it will be observed that the flues were distorted with one-third the pressure required to rupture the external shell.

These boilers were made for the North-Eastern Division of the London and North-Western Railway Company,

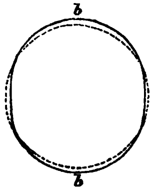
Fig. 2.



and were respectively of 35 and 25 feet in length. They were 7 feet in diameter, and composed of plates $\frac{3}{8}$ths of an inch thick. Each boiler had two cylindrical flues 3 feet 6 inches in diameter, and of the same thickness of plates

as the outer shell. They were fixed in the position shown in the annexed diagram, and were intended to resist an ordinary working pressure of only 40 lbs. upon the square inch. In submitting them to the usual test of double pressure, the flues of the first or longest boiler gave way with 97 lbs. upon the square inch; and those of the shorter boiler required 127 lbs. to effect the same distortion. With these large tubes a complete collapse was not accomplished, but the circular form, indicated by the dotted line, was *distorted*, and the flue became elliptical, as shown at *b b**.

Fig. 3.



The weakness of the flues in the above experiments is so evident as to need no comment. To

* Reducing the above results to unity of length, which with flues of this size should give a nearly constant quantity, we have—

	D.	L.	P.	P.L.
First boiler . . .	42	35	97	3395
Second boiler . .	42	25	127	3175

The correspondence in the last column shows that these flues obey the law of inversely as the lengths, very nearly, in their powers of resistance.

It may be well to test the accuracy of the formula which has been found to apply to tubes of a length not greater than 10 feet, by determining from it the strength of flues similar to the above, and comparing the results with those derived from experiment.

Here, for the boiler 35 feet long, we have by formula

$$P = 806{,}300\frac{k^2}{LD},$$

$$= 78 \text{ lbs.}; \text{ by experiment } 97 \text{ lbs.}$$

This difference confirms the view already stated, that the formula for short tubes does not apply *strictly* to tubes longer than 10 feet.

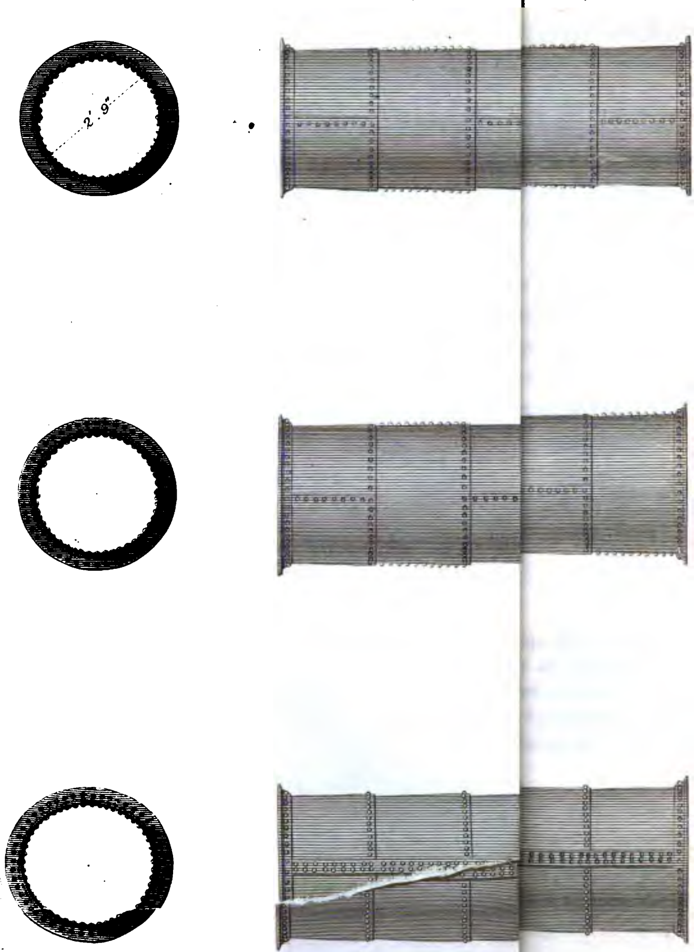
For the boiler 25 feet long, we have

$$P = 109 \text{ lbs.}; \text{ by experiment } 127 \text{ lbs.}$$

A less difference between the experimental and calculated result, as would have been anticipated from the shorter length of the flue.

It will be observed, that even these experiments, upon full sized boilers, are remarkably consistent, and offer no discrepancies which cannot be easily explained consistently with the general formula.

Plate II.



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er flues,

Ske ts .

remedy it, it has been already stated, we need only resort to a construction so simple, and yet so effective, as to meet at a small expense all the requirements of the case.

Figure 1, Plate II., exhibits an ordinary boiler flue, 30 feet long and 2 feet 9 inches in diameter, with simple lap-joints, as hitherto invariably constructed. To attain nearly three times the strength of this, it will only be necessary to introduce two or more strong, rigid, angle or T iron ribs, as exhibited in figs. 2 and 3, at *a*, *a*. This arrangement will not only remove all doubts as to the strength of these flues, by bringing them within the limits to which the formula applies with strictness, but will give to flues 30 feet long a strength equivalent to that of flues only 10 feet long, and make them uniform in their powers of resistance with the other parts of the boiler.

The reduction of the strength of flues by the lap-joints has already been stated; the deviation from the true cylindrical form which they cause, lessens, in some cases, seriously the strength of the vessels, as may be seen in Experiments 23 and 24, Table VI. Hence it is also proposed that flues required to resist an external pressure should be formed with double-riveted *butt-joints*, with longitudinal covering plates, as shown at *b*, *b*, *b*, fig. 3, Plate II. It is believed that these alterations will secure ample safety in these important constructions, and in this trust they are commended to the attention of the engineer and the public generally.

II.

RESEARCHES ON THE RESISTANCE OF GLASS GLOBES AND CYLINDERS TO COLLAPSE FROM EXTERNAL PRESSURE; AND ON THE TENSILE AND COMPRESSIVE STRENGTH OF VARIOUS KINDS OF GLASS.*

(Reprinted from the Transactions of the Royal Society, 1859.)

THE recently published experiments upon the collapse of tubes of wrought iron, led to results so novel and so much at variance with the ordinary rules of practice, as to exemplify anew the caution and diligence which are requisite in investigating the physical laws of nature, in order to arrive at just conclusions in regard to the properties of materials and their most effective distribution for the purposes of construction.

In the experiments alluded to it was clearly shown that the prevailing ideas of the strength of vessels subjected to a uniform external force were erroneous, and at variance with the laws of resistance to collapse under such circumstances; whilst in practice the prevalence of error in this matter had led to serious and sometimes fatal accidents, arising out of the construction of vessels of inadequate strength to sustain the pressures placed upon them. These errors, it is hoped, need no longer be perpetuated, and in order to give them as wide a circulation as possible, I have—with the permission of the Council of the Royal

* These experiments were carried on in conjunction with T. Tate, Esq., but are reprinted here on account of their connection with, and confirmation of, the experiments in the preceding paper.

Society—introduced the experiments in full and in such a form as will give to the general reader a distinct idea of the principles necessary to be observed in constructions which involve considerations of such vast importance to the practical engineer, in addition to the increased security of life and property.

The experiments on wrought iron, therefore, indicated a means of increasing the strength of boiler flues and other vessels of that material, subjected to a collapsing force, to any required amount; and this was the immediate practical application of the general law then discovered, that the strength of cylindrical vessels exposed to a uniform external force varied inversely as the length between the rigid ends.

The results deduced from the experiments on tubes composed of riveted plates were so important as to suggest further inquiry, under the same conditions of rupture, but with other materials, differing in their physical properties from wrought iron. The joints in the tubes employed in those experiments were defects, the influence of which might be determined by experiments upon homogeneous vessels. The ductile yielding character of wrought iron suggested the extension of the experiments to hard rigid materials, more capable of retaining their form under pressure.

To fulfil the conditions thus sought for, *glass* was selected for experiment, as a material differing totally in character from wrought iron, and on that account well fitted to supply data for extending our knowledge of the laws of collapse. Of vitreous structure, rigid, elastic, and brittle, and of low tenacity, it possessed the further advantage of being easily obtained and blown into homogeneous vessels of the required forms. But there were other reasons which had weight in making this selection. Our acquaintance with the strength of glass, in the various

forms in which it is employed in the arts and in scientific research, is very limited, and often as it is employed in circumstances in which it is exposed to pressure, few attempts have been made to register observations of its strength. Some researches on the density of steam at high pressures, now in progress, led to an examination of the subject, and added, to other reasons for testing its powers of resistance, the immediate necessity of knowing more of its properties before it could be trusted in those experimental inquiries.

Our knowledge of the cohesive properties of glass is so defective, that, to arrive at satisfactory and complete results, it was deemed advisable to ascertain by direct experiment its tenacity, or resistance to a tensile strain, its resistance to a crushing force, and, in the form of globes and cylinders, to determine its resistance to an internal bursting force, and to an external pressure tending to produce rupture by collapse. The results of the experiments upon glass globes and cylinders will, it is believed, form decided contributions to our present knowledge relative to the laws which determine the strength of materials. One remarkable result is that the law expressing the resistance of glass cylinders to compression is precisely similar to that which has been established for sheet-iron cylinders.

The glass experimented upon was of three kinds, known commercially as

Best Flint-glass,
Common Green Glass, and
Extra White Crown-glass.

The flint-glass obtained from Messrs. Molineaux, Webb, and Co., Manchester, was made of sand, oxide of lead, and carbonate of potash, in the following proportions:—

Sand	54 per cent.
Red oxide of lead . .	22 per cent.
Carbonate of potash .	24 per cent.

This glass is of a fine transparent character, fusible, and of a high specific gravity, due to the large per centage of lead in its composition.

The green and crown-glass were obtained from Messrs. Chance Brothers, of Birmingham, and were made of sand, soda, and lime, in the following proportions:—

Common Green Glass.

Sand	100 parts.
Sulphate of soda . . .	42 parts.
Carbonate of lime . . .	45 parts.

This is a hard infusible glass of a green colour, transparent, but of a less density than the flint-glass.

White Crown-glass.

Sand	100 parts.
Carbonate of soda . . .	38 parts.
Lime	11 parts.

A clear transparent glass, hard under the action of the grindstone, and highly infusible.

The specific gravity of these different kinds of glass varies greatly; the following Table gives the result of several determinations:—

Specific Gravity of Glass.

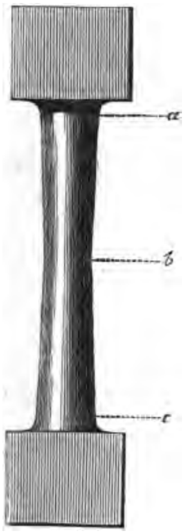
		Mean.
Best flint-glass . .	3·0787	3·0782
Best flint-glass . .	3·0777	
Common green glass .	2·5279	2·5284
Common green glass .	2·5289	
White crown-glass .	2·4498	2·4504
White crown-glass .	2·4510	

SECTION I.

TENACITY OF GLASS.

A few experiments were made upon the tenacity of glass, by tearing specimens asunder by a direct tensile strain. These results, however, owing to the following circumstances, are not so satisfactory as could be wished. In breaking glass by the method adopted for other materials, viz. by suspending weights to it, there is danger that its great rigidity and brittleness may occasion its fracture before the entire cohesive force has been balanced by the strain applied, from the vibration of laying on the weights. In the experiments upon globes, however, in which a uniform water pressure was employed, the tenacity of the glass was ascertained with more accuracy, and any failure in the present experiments is, therefore, the less to be regretted. The glass to be broken by a tensile strain was obtained of the form shown in fig. 4, drawn smaller at the middle to secure fracture at that part. These specimens were fixed in a pair of wrought-iron shackles, and rested by their shoulders upon a thick india-rubber washer placed on the turned faces of the shackles. In this state they were suspended to a firm support, and a scale-pan attached to the lower shackle. Weights were then added, with the greatest care, till the specimen fractured. In this manner the following results were obtained :—

Fig. 4.



EXPERIMENT 1.

Annealed Flint-glass.

Least diameter . . 0·57 in.
Least area . . . 0·255 sq. in.
Breaking weight, 583 lbs. = 2286 lbs. per square inch.

The fracture took place at *a*, fig. 4, and presented a regular smooth convex surface. No notch had been cut in this specimen.

EXPERIMENT 2.

Annealed Flint-glass.

Least diameter . . 0·50 in.
Least area . . . 0·196 sq. in.
Breaking weight, 499 lbs. = 2540 lbs. per square inch.

Broke in the notch at *b*, fig. 4, which in this case was cut by the grindstone. It is possible that the exterior coat of glass may be stronger than its core, in which case the above specimen was weakened. In the next experiments the specimens were drawn thinner by heat.

EXPERIMENT 3.

Common Green Glass.

Least diameter . . 0·53 in.
Least area . . . 0·220 sq. in.
Breaking weight, 639 lbs. = 2896 lbs. per square inch.

EXPERIMENT 4.

White Crown-glass.

Least diameter . . 0·54 in.
Least area . . . 0·229 sq. in.
Breaking weight, 583 lbs. = 2545 lbs. per square inch.

Broke at shoulder *a*, fig. 1.

The following Table exhibits at one view the results of these experiments, which, notwithstanding the objections to the method by which they were obtained, appear to be consistent with each other.

TABLE I.—*Tensile Strength of Glass Bars.*

Description of Glass.	Area of Specimen, in inches.	Breaking Weight, in lbs.	Tenacity per square inch.	
			in lbs.	in tons.
Flint-glass	0·255	583	2286	1·02
	0·196	499	2540	1·13
Green glass . . .	0·220	639	2896	1·29
Crown-glass . . .	0·229	583	2546	1·14

It may be observed here, in anticipation, that the tensile strength is much smaller in the case of glass fractured by a direct strain in the form of bars, than when burst by internal pressure in the form of thin globes. This difference is no doubt mainly due to the fact that thin plates of this material generally possess a higher tenacity than stout bars, which, under the most favourable circumstances, may be but imperfectly annealed. There is also a considerable discrepancy between the strength of green and crown-glass when in the form of bars and when in the form of globes. In the case of the bars, the results are as 1·0 to 1·13 in favour of green glass, whilst in the case of the globes, the results are as 1·0 to 1·2 in favour of the crown-glass. These discrepancies may, however, be accounted for from the different condition of the material in relation to annealing in the two cases, or from an imperfect bedding of the specimen, causing a distortion of the strain out of the direction of the axis of the specimen, or from accidental vibration in laying on the weights.

SECTION II.

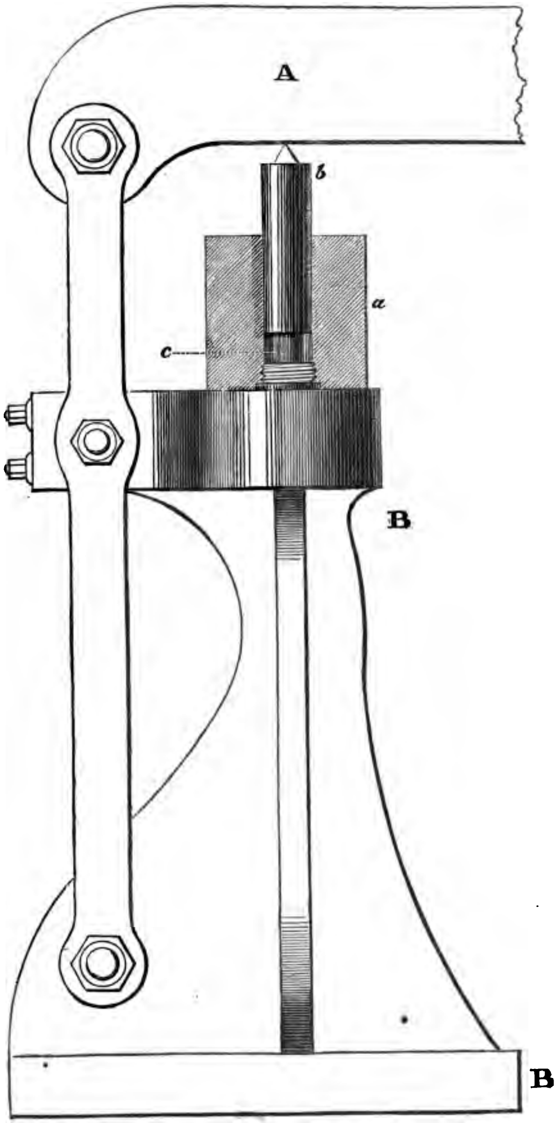
RESISTANCE OF GLASS TO CRUSHING.

The next series of experiments was instituted with a view of determining the powers of resistance of glass to a direct crushing force. The specimens subjected to experiment were small cylinders (fig. 5) varying in length from

Fig. 5.

1 to 2 inches, and about three-quarters of an inch in diameter. They were placed for the purpose of crushing within the box *a* (fig. 6), thin packings of soft lead being interposed between the glass and the parallel crushing surfaces of the box and its solid steel piston *b*; in this way a firm and uniform bearing surface was secured, and the crushing force was applied perpendicularly in the direction of the axis of the specimen. Fig. 6 exhibits the general arrangement of the crushing apparatus, consisting of a lever A, 8 feet long, supported on a strong cast-iron base B, B. The crushing force obtained by placing weights in the scale-pan hung at the extremity of the lever is transmitted through the piston *b*, to the specimen to be crushed, *c*.

Fig. 6.



Scale. 2 ins = 1 Ft.

Flint-glass Cylinders.

EXPERIMENT 1.

Diameter . . . 0·85 inch.
Area . . . 0·5674 square inch.
Height . . . 1·0 inch.
Placed between india-rubber packings.

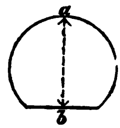
This specimen having been slightly fractured at an early stage in the experiment, it was taken out and the fractured side ground flat preparatory to another trial.

EXPERIMENT 2.

The same specimen as in Experiment 1.

Diameter . . . . 0·85 inch.
Height of segment (*ab*) . 0·73 inch.
Area . . . . . 0·555 inch.
Height of specimen. . 1·0 inch.

Fig. 7.



Weights added, in lbs.	Total weight, in lbs.	Weights added, in lbs.	Total weight, in lbs.
1321	1321	224	10569
2080	3401	224	10793
896	4297	224	11017
896	5193	224	11241
896	6089	224	11465
896	6985	224	11689
896	7881	224	11913
448	8329	224	12137
448	8777	224	12361
448	9225 Fractured	224	12585
224	9449	112	12697
224	9673	112	12809
224	9897	112	12921
224	10121	112	13033 Crushed
224	10345		

Fractured with 9,225 lbs. = 16,621 lbs. per square inch.
Crushed with 13,033 lbs. = 23,483 lbs. per square inch.

It will not be necessary again to repeat in detail the steps by which the weights were augmented, as these were similar in every case. In the succeeding experiments the weights at which the specimens fractured and crushed are alone given.

Experiment 3.

Diameter . . .	0·69 inch.
Area . . .	0·3739 square inch.
Height . . .	1·0 inch.

Fractured with 11,465 lbs.=30,661 lbs. per square inch.
Crushed with 13,033 lbs. =34,854 lbs. per square inch.

Experiment 4*.

Diameter . . .	0·70 inch.
Area . . .	0·3848 square inch.
Height . . .	1·55 inch.

Crushed suddenly with 5193 lbs.=13,494 lbs. per square inch.

Experiment 5.

Diameter . . .	0·83 inch.
Area . . .	0·541 square inch.
Height . . .	1·6 inch.

Crushed suddenly with 11,241 lbs.=20,775 lbs. per square inch.

Experiment 6.

Diameter . . .	0·68 inch.
Area . . .	0·3631 square inch.
Height . . .	2·05 inches.

Crushed with 11,913 lbs.= 32,803 lbs. per square inch.

* This experiment is so evidently anomalous, that there can be little doubt that the bedding surfaces were not parallel; hence this result is omitted in the following averages.

Green Glass Cylinders.

EXPERIMENT 7.

Diameter . . .	0·77 inch.
Area . . .	0·466 square inch.
Height . . .	1·0 inch.

Fractured with 6933 lbs. = 14,888 lbs. per square inch.
Crushed with 10,516 lbs. = 22,583 lbs. per square inch.

EXPERIMENT 8.

Diameter . . .	0·76 inch.
Area . . .	0·454 square inch.
Height . . .	1·5 inch.

Fractured with 8126 lbs. = 17,883 lbs. per square inch.
Crushed with 15,891 lbs. = 35,029 lbs. per square inch.

EXPERIMENT 9.

Diameter . . .	0·79 inch.
Area . . .	0·4901 square inch.
Height . . .	2·0 inches.

Sustained a weight of 18,634 lbs. = 38,015 lbs. per square inch, without being crushed. At this point the deflection of the lever was so great, that it was considered dangerous to proceed. On removing the specimen to a heavier lever, it crushed with a force of 12,000 lbs. The larger weight, however, had been fairly supported.

Crown-glass Cylinders.

The two cylinders of crown-glass were slightly rounded towards the edge of the bearing surfaces, which reduced the area directly subjected to the crushing force. It is therefore probably most accurate to take the less area in reducing the results.

EXPERIMENT 10.

Diameter . . . { 0·72 inch at middle. 0·68 inch at ends.
Area . . . 0·363 square inch.
Height . . . 1·5 inch.
Crushed suddenly with 14,100 lbs. = 38,825 lbs. per square inch.

EXPERIMENT 11.

Diameter . . . { 0·80 inch at middle. 0·76 inch at ends.
Area . . . 0·454 square inch.
Height . . . 1·0 inch.
Crushed suddenly with 10,516 lbs. = 23,181 lbs. per square inch.

Arranging the above results together, we obtain the following general Table of the results of the experiments:—

TABLE II.—*Summary of Results of Experiments on the Resistance of Annealed Glass Cylinders to Crushing.*

Description of Glass.	Height of Cylinder in inches.	Area of Cylinder, in inches.	Weight causing Fracture, in lbs.	Crushing Weight in lbs.	Weight per sq. in. to cause Fracture, in lbs.	Weight per sq. in. to Crush, in lbs.
Flint-glass	1·00	0·555	9,225	13,033	16,621	23,483
	1·00	0·374	11,465	13,033	30,661	34,854
	1·60	0·541	. .	11,241	. .	20,775
	2·05	0·363	. .	11,913	. .	32,803
Green glass . . .	1·00	0·466	6,933	10,516	14,888	22,583
	1·50	0·454	8,126	15,891	17,883	35,029
	2·00	0·490	. .	18,634	. .	38,015
Crown-glass . . .	1·0	0·454	. .	10,516	. .	23,181
	1·5	0·363	. .	14,100	. .	38,825

Taking the means of the above values, and reducing the weights to tons, we have:—

TABLE III.—*Mean Compressive Resistance of Glass.*

Description of Glass.	Height of Cylinder in inches.	Crushing Weight per square inch,		Mean crushing Weight per square inch,	
		in lbs.	in tons.	in lbs.	in tons.
Flint-glass . .	1·0 1·6 2·0	29,168 20,775 32,803	13·021 9·274 14·644	27,582	12·313
Green glass. .	1·0 1·5 2·0	22,583 35,029 38,015	10 081 15·628 16·971	31,876	14·227
Crown-glass . .	1·0 1·5	23,181 38,825	10·348 17·332	31,003	13·840

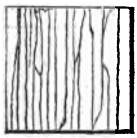
The mean resistance of glass to a crushing force is, therefore, from the above experiments, equivalent to 13·460 tons per square inch. Assuming the above numbers to represent the comparative values of each kind of glass, and taking flint-glass as the standard, we have their respective strengths as follow :—

Green glass . . .	1152
Crown-glass . . .	1124
Flint-glass . . .	1000

The specimens were crushed almost to powder from the violence of the concussion, when they gave way; it however appeared that the fractures occurred in vertical planes, splitting up the specimen in all directions. This characteristic mode of disintegration has been noticed before, especially with vitrified brick and indurated limestone. The experiments following on cubes of glass, which were exposed to view during the crushing process, illustrated this subject further: cracks were noticed to form some time before the specimen finally gave way; then

these rapidly increased in number, splitting the glass into innumerable irregular prisms of the same height as the cube; finally these bent or broke, and the pressure, no longer bedded on a firm surface, destroyed the specimen.

Fig. 8.



The annexed ideal sketch (fig. 8) may give some notion of the fractures of a cube, supposing all the particles were restored to their position after crushing.

The specimens employed in the following experiments were cut from the square heads of the pieces of glass employed in the experiments on tensile strain (fig. 4). These pieces were approximately cubical, and their size prevented their insertion in the box *a* (fig. 6); they were, therefore, crushed between parallel steel discs, exposed to view. The crushing was more gradual, and was not effected so completely in these experiments as in those on small cylinders, the fragments being in every case larger after the conclusion of the experiment: it must further be recollected, in comparing these with the preceding experiments, that the cylinders were cut off, of the required length, from rods of glass drawn out when molten to the diameter desired, so as to retain the first-cooled exterior skin of glass, which is probably of greater tenacity than the interior; on the other hand, the cubes were cut from the centre of larger lumps of glass, and were possibly in a state of imperfect annealing.

Flint-glass Cubes.

Experiment 12.

Area $= 0{\cdot}96 \times 0{\cdot}97$ inch $= 0{\cdot}9312$ square inch.
Height $= 1{\cdot}15$ inch.

Crushed suddenly with 13,257 lbs. = 14,235 lbs. per square inch.

EXPERIMENT 13.

Area = 0·99 × 0·98 inch = 0·9702 square inch.
Height = 1·16 inch.
Crushed with 12,809 lbs. = 13,202 lbs. per square inch.

EXPERIMENT 14.

Area = 0·98 × 1·02 inch = 0·9996 square inch.
Height = 1·10 inch.
Crushed with 13,257 lbs. = 13,262 lbs. per square inch.

EXPERIMENT 15.

Area = 0·98 inch × 0·98 in. = 0·9604 square inch.
Height = 1·10 inch.
Fractured with 6537 lbs. = 6806 lbs. per square inch.
Crushed with 11,353 lbs. = 11,820 lbs. per square inch.

Green Glass Cubes.

EXPERIMENT 16.

Area = 1·0 × 0·98 inch = 0·98 square inch.
Height = 1·0 inch.
Crushed with 20,059 lbs. = 20,468 lbs. per square inch.

EXPERIMENT 17.

Area = 0·99 × 1·2 inch = 1·188 square inch.
Height = 1·0 inch.
Crushed with 23,535 lbs. = 19,945 lbs. per square inch.

Crown-glass Cube.

EXPERIMENT 18.

Area = 0·82 × 0·92 inch = 0·7534 square inch.
Height = 0·9 inch.
Crushed with 16,475 lbs. = 21,867 lbs. per square inch.

This crushed suddenly after bearing the weight some time, and was reduced almost to powder.

TABLE IV.—*Summary of the Results of Experiments on the Resistance of Cut Glass Cubes to Compression.*

Description of Glass.	Area of Specimen, in square inch.	Crushing Weight in lbs.	Resistance to Crushing per square inch,	
			in lbs.	in tons.
Flint-glass . . .	0·9312	13,257	14,235	6·355
	0·9702	12,809	13,202	5·894
	0·9996	13,257	13,262	5·921
	0·9604	11,353	11,820	5·276
Green glass . . .	0·9800	20,059	20,468	9·116
	1·1880	23,535	19,945	8·904
Crown-glass . . .	0·7534	16,475	21,867	9·762

Hence the mean resistance to crushing of cubes of glass is equivalent to a weight of—

		lbs.
For flint-glass	. .	13,130
For green glass	. .	20,206
For crown-glass	. .	21,867
Mean	. .	18,401

Comparing these with the preceding results on glass cylinders, we have the mean resistance of the former experiments to the mean resistance of the above as 30,153 : 18,401, or as 1·6 : 1.

General Observations relative to the Results of the Experiments on the Resistance of Glass Cylinders and Cubes to Crushing.

With iron and some other materials, when a short column undergoes a pressure in the direction of its length, rupture takes place in a plane having a determinate angle to the axis of the column, this plane being the section of least resistance. Neglecting the friction of the surfaces,

Coulomb found this angle to be 45°, and allowing on an average 10° for the limiting angle of friction, the angle of the plane of rupture may be taken at 55°. To fulfil this condition, the length of the column to be crushed should be at least three times its radius: when the length greatly exceeds this limit, the rupture will be effected by the tendency of the column to bend; and when the length is within this limit, the force requisite to produce rupture will be increased in consequence of the irregular form of the line of fracture. These theoretical deductions have been confirmed by experiments made upon columns of iron, wood, bone, stone, and other materials. The results of the experiments here recorded, however, show that when the length of the cylinder does not greatly differ from three times its radius, the resistance to a crushing force is pretty nearly a constant, viz. on an average 12·313 tons per square inch in the case of flint-glass, 14·227 tons in the case of green glass, and 13·84 tons in the case of crown-glass. But, according to Coulomb's law, the cubes of flint-glass (their lengths being considerably less than three times their semi-diameters) should have presented higher powers of resistance than the cylinders; this discrepancy is probably owing to the injury which the glass had sustained in the process of cutting, and to the imperfect annealing of glass when cast in the form of cubes and cylinders.

SECTION III.

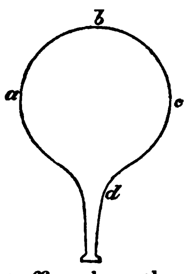
RESISTANCE OF GLASS GLOBES AND CYLINDERS TO INTERNAL PRESSURE.

In the following experiments it has been sought not only to determine the law of resistance to internal pressure, which is already well known from theoretical con-

siderations, but to ascertain the direct tensile strength of the glass (of which the bursting pressure is a function) by a method free from many of the objections to that described in Section I. The bursting pressure of cylindrical and spherical vessels is well known to be in the ratio of the tenacity of the material, other things being the same, and the determination of the tensile strength upon this principle presents in the case of glass peculiar advantages. As glass can be obtained in tolerably perfect spheres, and as the fracture of these may be effected by a uniform water pressure, increasing slowly and regularly without vibration, there is a better chance of ascertaining the ultimate resistance of the material, from the absence of those shocks and irregularities which are inseparable from any process depending upon the piling up of weights, however carefully conducted.

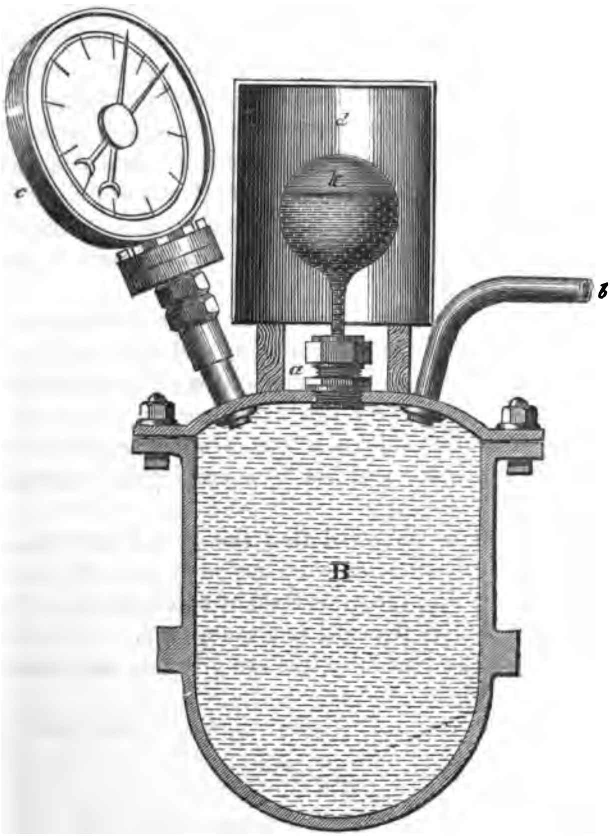
In making these experiments, a number of glass globes were procured of varying size and thickness. The stems were then flanched out by the blowpipe (fig. 9), and the diameter having been carefully measured, they were ready for experiment. To effect their rupture, each globe, *k* (fig. 10), was attached by means of a stuffing-box (*a*) to the cover of a strong wrought-iron boiler B, and was enclosed by the iron cylindrical vessel *d*, to prevent the dispersion of the fragments when rupture took place. In the stuffing-box the flanch of the stem of the globe was bedded upon vulcanised india-rubber in such a manner as to secure a water-tight attachment without impeding the access of the water to the interior of the globe. The boiler was connected with a hydraulic pump by means of the pipe *b*, and an accurate gauge of the Schaeffer construction was fixed to the boiler to register the pressure. With this arrangement it will be seen that as the pumping was con-

Fig. 9.



tinued the water would rise in the globe, compressing the air in its interior, progressively, up to the point at which the resistance of the glass was overcome by the expansive force of the fluid; at that point explosion would take place, the pressure in pounds per square inch being noted both by the eye of the observer and by the maximum finger of the gauge.

Fig. 10.



In glass globes generally, the upper half of the sphere *a, b,* c (fig. 9) is the most spherical, and is approximately uniform in thickness, being, however, thinnest at *b,* and thickening gradually downwards towards the stem, the lower half (*a, d, c*) being considerably the strongest. Hence it happened, in several cases (in fact in every case in which the point could be determined with certainty from the condition of the fragments), that the globes ruptured first at *b,* the lines of fracture radiating in every direction, passing round the globe as meridians of longitude, and splitting it up into thin bands, varying from $\frac{1}{20}$th to $\frac{1}{8}$th inch in width. In the case of some elongated ellipsoids, it appeared that the fractures occurred horizontally, or perhaps obliquely, from the condition of the fragments attached to the stem. In most cases, however, it was not clear from the fragments which had been the direction of the fracture, although the mode of rupture was the same in every case.

To ascertain the thickness, several specimens were selected from the thinnest fragments, and each being measured separately by a micrometer screw of fifty threads to the inch and reading on a graduated head to $\frac{1}{5000}$th of an inch, the minimum thickness was assumed as that of the part which ruptured, and has been employed in reducing the results.

It must also be observed that the globes were usually slightly elliptical, in some cases seriously so; the vertical diameter, *b d* (using the same form of expression as before) being generally less than the horizontal, *a c.* In the following Tables the two diameters are given in each case :—

Flint-glass.

Experiment 1.

Globe a. Diameters 4·0 and 3·98 inches.

$$\text{Thicknesses measured}\left\{\begin{array}{l}\text{In parts of an inch.}\\0{\cdot}0230\\0{\cdot}0256\\0{\cdot}0284\\0{\cdot}0244\\0{\cdot}0302\\0{\cdot}0250\\0{\cdot}0240\end{array}\right\}\text{Minimum}=0{\cdot}024\text{ inch.}$$

Bursting pressure = 84 lbs. per square inch.

3504 lbs. pr. sq. in. of section

Experiment 2.

Globe b. Diameters 4·0 and 3·98 inches.

$$\text{Thicknesses measured}\left\{\begin{array}{l}\text{In parts of an inch.}\\0{\cdot}034\\0{\cdot}032\\0{\cdot}031\\0{\cdot}0254\\0{\cdot}0256\\0{\cdot}031\\0{\cdot}028\end{array}\right\}\text{Minimum}=0{\cdot}025\text{ inch.}$$

Bursting pressure = 93 lbs. per square inch.

3720 lbs. pr. sq. in.

Experiment 3.

Globe c. Diameter 4·0 inches.

$$\text{Thicknesses measured}\left\{\begin{array}{l}\text{In parts of an inch.}\\0{\cdot}040\\0{\cdot}0406\\0\ 039\\0{\cdot}039\\0{\cdot}038\end{array}\right\}\text{Minimum}=0{\cdot}038\text{ inch.}$$

Bursting pressure = 150 lbs. per square inch.

3947 pr. sq. in.

Experiment 4.

Globe d. Diameters 4·5 and 4·55 inches.

In parts of an inch.

$$\text{Thicknesses measured}\left\{\begin{array}{l}0{\cdot}0620\\0{\cdot}0694\\0{\cdot}0584\\0{\cdot}0626\\0{\cdot}0564\\0{\cdot}0614\\0{\cdot}0604\\0{\cdot}0580\end{array}\right\}\text{Minimum}=0{\cdot}056\text{ inch.}$$

Burst with 280 lbs. per square inch.

Experiment 5.

Globe e. Diameters 5·1 and 5·12 inches.

In parts of an inch.

$$\text{Thicknesses measured}\left\{\begin{array}{l}0{\cdot}0580\\0{\cdot}059\\0{\cdot}0586\\0{\cdot}0634\\0{\cdot}0620\\0{\cdot}059\end{array}\right\}\text{Minimum}=0{\cdot}058\text{ inch.}$$

Burst with 184 lbs. per square inch.

Experiment 6.

Globe f. Diameter 6·0 inches.

In parts of an inch.

$$\text{Thicknesses measured}\left\{\begin{array}{l}0{\cdot}060\\0{\cdot}066\\0{\cdot}060\\0{\cdot}059\\0{\cdot}0592\\0{\cdot}0592\end{array}\right\}\text{Minimum}=0{\cdot}059\text{ inch.}$$

Burst with 152 lbs. per square inch.

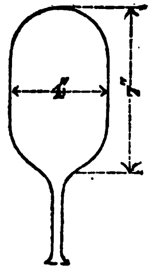
Experiment 7.

Cylinder g. Diameter 4·05 inches. Length 7·0 inches.

In parts of an inch.

$$\text{Thicknesses measured}\left\{\begin{array}{l}0{\cdot}079\\0{\cdot}081\\0{\cdot}090\\0{\cdot}086\\0{\cdot}086\\0{\cdot}079\\0{\cdot}086\end{array}\right\}\begin{array}{l}\text{Minimum}\\=0{\cdot}079\\\text{inch.}\end{array}$$

Fig. 11.



Burst with 282 lbs. per square inch.

Green Glass.

Experiment 8.

Globe k. Diameters 4·95 and 5·0 inches.

In parts of an inch.

$$\text{Thicknesses measured}\left\{\begin{array}{l}0{\cdot}029\\0{\cdot}024\\0{\cdot}026\\0{\cdot}022\\0{\cdot}025\\0{\cdot}023\\0{\cdot}024\\0{\cdot}0225\end{array}\right\}\text{Minimum}=0{\cdot}022\text{ inch.}$$

Bursting pressure = 90 lbs. per square inch.

Experiment 9.

Globe l. Diameters 4·95 and 5·0 inches.

In parts of an inch.

$$\text{Thicknesses measured}\left\{\begin{array}{l}0{\cdot}024\\0{\cdot}023\\0{\cdot}022\\0{\cdot}0196\\0{\cdot}023\\0{\cdot}022\\0{\cdot}020\\0{\cdot}020\end{array}\right\}\text{Minimum}=0{\cdot}020\text{ inch.}$$

Burst with 85 lbs. per square inch.

Experiment 10.

Globe m. Diameters 4·0 and 4·05 inches.

In parts of an inch.

$$\text{Thicknesses measured}\left\{\begin{array}{l}0{\cdot}020\\0{\cdot}0205\\0{\cdot}0202\\0{\cdot}021\\0{\cdot}018\\0{\cdot}020\\0{\cdot}023\\0{\cdot}0205\\0{\cdot}0215\\0{\cdot}020\end{array}\right\}\text{Minimum}=0{\cdot}018\text{ inch.}$$

Bursting pressure = 84 lbs. per square inch.

Experiment 11.

Globe n. Diameters 4·0 and 4·03 inches.

In parts of an inch.

$$\text{Thicknesses measured}\left\{\begin{array}{l}0{\cdot}016\\0{\cdot}019\\0{\cdot}018\\0{\cdot}017\\0{\cdot}019\\0{\cdot}016\\0{\cdot}016\end{array}\right\}\text{Minimum}=0{\cdot}016\text{ inch.}$$

Bursting pressure = 82 lbs. per square inch.

Crown-glass.

Experiment 12.

Globe p. Diameters 4·2 and 4·35 inches.

In parts of an inch.

$$\text{Thicknesses measured}\left\{\begin{array}{l}0{\cdot}0252\\0{\cdot}0270\\0{\cdot}0272\\0{\cdot}030\\0{\cdot}0252\\0{\cdot}0256\end{array}\right\}\text{Minimum}=0{\cdot}025\text{ inch.}$$

Burst with 120 lbs. per square inch.

Experiment 13.

Globe q. Diameters 4·05 and 4·20 inches.

In parts of an inch.

$$\text{Thicknesses measured}\left\{\begin{array}{l}0{\cdot}028\\0{\cdot}0236\\0{\cdot}0256\\0{\cdot}0236\\0{\cdot}0212\\0{\cdot}0210\end{array}\right\}\text{Minimum}=0{\cdot}021\text{ inch.}$$

Bursting pressure = 126 lbs. per square inch.

Experiment 14.

Globe r. Diameters 5·9 and 5·8 inches.

In parts of an inch.

$$\text{Thicknesses measured}\left\{\begin{array}{l}0{\cdot}0334\\0{\cdot}020\\0{\cdot}0244\\0{\cdot}017\\0{\cdot}0172\\0{\cdot}016\end{array}\right\}\text{Minimum}=0{\cdot}016\text{ inch.}$$

Burst with 69 lbs. per square inch.

Experiment 15.

$$\textit{Globe s.}\quad\text{Diameters}\left\{\begin{array}{l}\text{horizontal}=6{\cdot}0\text{ inches.}\\\text{vertical}\quad=6{\cdot}3\text{ inches.}\end{array}\right.$$

In parts of an inch.

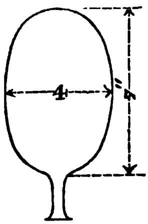
$$\text{Thicknesses measured}\left\{\begin{array}{l}0{\cdot}024\\0{\cdot}020\\0{\cdot}0228\\0{\cdot}0204\\0{\cdot}0270\\0{\cdot}0262\end{array}\right\}\text{Minimum}=0{\cdot}020\text{ inch.}$$

Bursting pressure = 86 lbs. per square inch.

Experiment 16.

Ellipsoid t. Diameters 4·1 and 7·0 inches.

Fig. 12.



$$\text{Thicknesses measured}\left\{\begin{array}{l}\text{In parts of an inch.}\\ 0{\cdot}0180\\ 0{\cdot}0208\\ 0{\cdot}0220\\ 0{\cdot}0160\\ 0{\cdot}0184\\ 0{\cdot}0170\\ 0{\cdot}0220\end{array}\right\}\text{Minimum } 0{\cdot}016 \text{ inch.}$$

Bursting pressure = 80 lbs. per square inch.

Experiment 17.

Ellipsoid v. Diameters 4·0 and 7·0 inches.

$$\text{Thicknesses measured}\left\{\begin{array}{l}\text{In parts of an inch.}\\ 0{\cdot}0206\\ 0{\cdot}0208\\ 0{\cdot}0224\\ 0{\cdot}0190\\ 0{\cdot}0206\\ 0{\cdot}022\\ 0{\cdot}021\\ 0{\cdot}0254\end{array}\right\}\text{Minimum} = 0{\cdot}019 \text{ inch.}$$

Bursting pressure = 109 lbs. per square inch.

Summing up the preceding results, they are arranged in the following Table:—

Summary of Results.

TABLE V.—*Resistance of Glass Globes to internal Pressure.*

Number of Experiment.	Description of Glass.	Diameter in inches.	Thickness in parts of an inch.	Bursting Pressure in pounds, per square inch.	pr. sq. in. of section
I.	Flint-glass	4·0 × 3·98	0·024	84	3504
II.	Flint-glass	4·0 × 3·98	0·025	93	3720
III.	Flint-glass	4	0·038	150	3947
IV.	Flint-glass	4·5 × 4·55	0·056	280	5625
V.	Flint-glass	5·1 × 5·12	0·058	184	4189
VI.	Flint-glass	6	0·059	152	3864
				Mean	4147
VIII.	Green glass	4·95 × 5·0	0·022	90	5113
IX.	Green glass	4·95 × 5·0	0·020	85	5312
X.	Green glass	4·0 × 4·05	0 018	84	4666
XI.	Green glass	4·0 × 4·03	0·016	82	5126
					5054 Mean
XII.	Crown-glass	4·2 × 4·35	0·025	120	5040
XIII.	Crown-glass	4·05 × 4·2	0·021	126	6000
XIV.	Crown-glass	5·9 × 5·8	0·016	69	6356
XV.	Crown-glass	6·0 × 6·3	0·020	86	6450
					Mean 5961

TABLE VI.—*Resistance of Glass Cylinders and Ellipsoids to internal Pressure.*

Number of Experiment.	Description of Glass.	Form of Vessel.	Diameter in inches.	Thickness, in parts of an inch.	Bursting Pressure, in pounds per square in.	
VII.	Flint-glass	Cylinder .	4·05 × 7·0	0·079	282	45[illegible]
XVI.	Crown-glass . . .	Ellipsoid . .	4·1 × 7·0	0·016	80	[illegible]
XVII.	Crown-glass . . .	Ellipsoid . .	4·1 × 7·0	0·019	109	

SECTION IV.

ON THE RESISTANCE OF GLASS GLOBES AND CYLINDERS TO AN EXTERNAL PRESSURE.

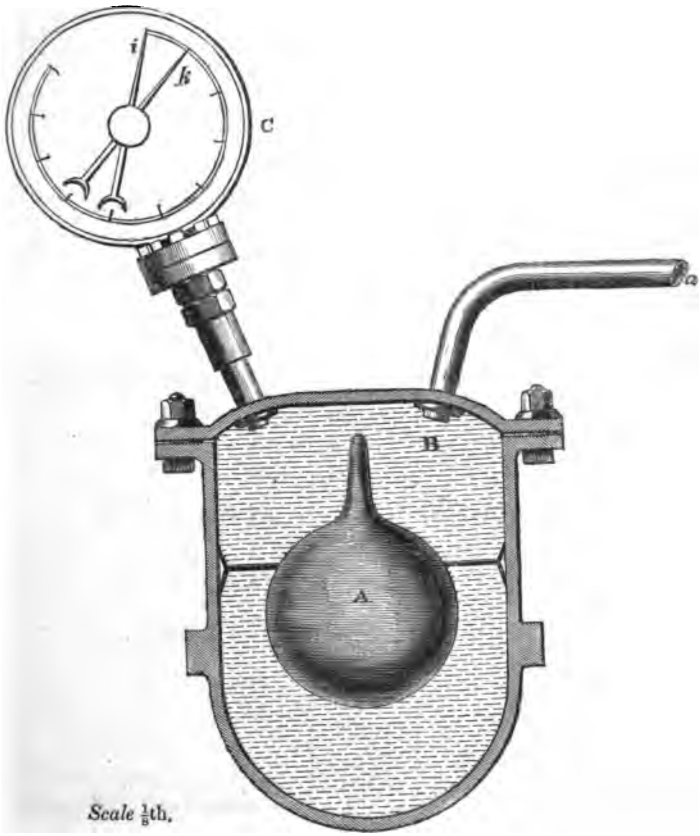
The following experiments are in continuation of, and supplementary to, the researches on the collapse of wrought-iron vessels already alluded to. In this aspect they are the most important in their bearings and the most novel of any in the present memoir.

The method of conducting them did not differ in any essential detail from that pursued in the researches upon wrought-iron tubes, described in a former paper. A number of globes of varying dimensions were procured, and hermetically sealed by means of the blowpipe. In this state they were fixed in the interior of the strong wrought-iron boiler B (fig. 10) (capable of sustaining a pressure of about 2500 lbs. per square inch), in the position shown at A. The boiler or vessel B communicated, by means of the pipe *a*, with a hydraulic force-pump having a plunger of three-quarters of an inch diameter, so that a uniform pressure of about 1000 lbs. per square inch could easily be obtained. In order to register the pressure, gauges of the Schaeffer construction* (C) were employed, as before, affording, within small limits of error, certain and accurate indications of the increase of pressure obtained by the pump. The collapse of the glass vessel was made known by a loud report, and by the instant recession of the moveable finger of the gauge *i*; the maximum pressure obtained was marked by a second finger *k*, and also, to prevent error from any accidental cause, by the eye of the observer.

* In pressure-gauges of the Schaeffer construction a corrugated steel plate measures the force, by expanding under pressure. The indications are communicated by a rack and pinion to the hand of the gauge which moves over a face plate graduated by trial. In principle this gauge does not materially differ from the aneroid barometer.

During the collapse the globes were reduced to the smallest fragments; in some cases a great part almost to powder, by the violence of the concussion. Hence in

Fig. 13.



these experiments no indication could be found of the mode in which the globes had given way, nor of the direction of the primary lines of fracture.

After the globe had been ruptured, the fragments were carefully collected, and a selection having been made of the thinnest, they were measured, as before, by means of a micrometer-screw. The minimum thickness thus determined has been assumed for the thickness of the point of rupture in the calculations.

Flint-glass.

Experiment 1.

Globe A. Diameters 5·05 and 4·76 inches.

$$\text{Thicknesses measured}\left\{\begin{array}{c}\text{In parts of an inch.}\\ 0{\cdot}0170\\ 0{\cdot}0192\\ 0{\cdot}0190\\ 0{\cdot}0218\\ 0{\cdot}0220\\ 0{\cdot}0146\\ 0{\cdot}0178\\ 0{\cdot}0154\end{array}\right\}\text{Minimum}=0{\cdot}014\text{ inch.}$$

Collapsing pressure = 292 lbs. per square inch.

Experiment 2.

Globe B. Diameters 5·08 and 4·7 inches.

$$\text{Thicknesses measured}\left\{\begin{array}{c}\text{In parts of an inch.}\\ 0{\cdot}0210\\ 0{\cdot}0200\\ 0{\cdot}0180\\ 0{\cdot}0200\\ 0{\cdot}0194\\ 0{\cdot}0188\\ 0{\cdot}0192\\ 0{\cdot}0196\end{array}\right\}\text{Minimum}=0{\cdot}018\text{ inch.}$$

Collapsing pressure = 410 lbs. per square inch.

Experiment 3.

Globe C. Diameters 4·95 and 4·72 inches.

$$\text{Thicknesses measured}\left\{\begin{array}{c}\text{In parts of an inch.}\\ 0{\cdot}0214\\ 0{\cdot}0246\\ 0{\cdot}0208\\ 0{\cdot}0220\\ 0{\cdot}0266\\ 0{\cdot}0222\\ 0{\cdot}0226\end{array}\right\}\text{Minimum} = 0\ 022\text{ inch.}$$

Collapsing pressure = 470 lbs. per square inch.

Experiment 4.

Globe D. Diameter 5·6 inches.
Minimum thickness = 0·020 inch.
Collapsing pressure = 475 lbs. per square inch.

Experiment 5.

Globe E. Diameters 8·22 and 7·45 inches.

$$\text{Thicknesses measured}\left\{\begin{array}{c}\text{In parts of an inch.}\\ 0{\cdot}0152\\ 0{\cdot}0118\\ 0\ 0122\\ 0{\cdot}0100\\ 0{\cdot}0106\\ 0{\cdot}0128\\ 0{\cdot}0108\\ 0{\cdot}0108\\ 0{\cdot}0110\\ 0{\cdot}0102\end{array}\right\}\text{Minimum} = 0{\cdot}010\text{ inch.}$$

Collapsing pressure = 35 lbs. per square inch.

Experiment 6.

Globe F. Diameters 8·2 and 7·2 inches.

$$\text{Thicknesses measured}\left\{\begin{array}{c}\text{In parts of an inch.}\\ 0{\cdot}0124\\ 0{\cdot}0138\\ 0{\cdot}0126\\ 0{\cdot}0116\\ 0{\cdot}0120\\ 0{\cdot}0120\end{array}\right\}\text{Minimum}=0{\cdot}012\text{ inch.}$$

Collapsing pressure = 42 lbs. per square inch.

Experiment 7.

Globe G. Diameters 8·2 and 7·4 inches.

$$\text{Thicknesses measured}\left\{\begin{array}{c}\text{In parts of an inch.}\\ 0{\cdot}0160\\ 0{\cdot}0144\\ 0{\cdot}0166\\ 0{\cdot}0148\\ 0{\cdot}0144\\ 0{\cdot}0158\\ 0{\cdot}0164\\ 0{\cdot}0150\end{array}\right\}\text{Minimum}=0{\cdot}015\text{ inch.}$$

Collapsing pressure = 60 lbs. per square inch.

Experiment 8.

Globe H. Diameters 4·0 and 3·98 inches.
Minimum thickness = 0·024 inch.

This globe sustained unbroken a pressure of 900 lbs. per square inch.

Experiment 9.

Globe I. Diameter 4·0 inches.
Minimum thickness = 0·025 inch.

This globe sustained unbroken a pressure of 900 lbs. per square inch.

Experiment 10.

Globe K. Diameter 6·0 inches.
Minimum thickness = 0·059 inch.

This globe remained unbroken with a pressure of 1000 lbs. per square inch.

Experiment 11.

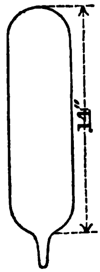
Cylinder L. Diameter 3·09 inches.
Length 14 inches.

In parts of an inch.

$$\text{Thicknesses measured}\left\{\begin{matrix}0\cdot0243\\0\cdot0241\\0\cdot0235\\0\cdot0238\\0\cdot0241\\0\cdot0352\end{matrix}\right\}\begin{matrix}\text{Minimum}\\=0\cdot024\text{ inch.}\end{matrix}$$

Collapsing pressure = 85 lbs. per square inch.

Fig. 14.



Experiment 12.

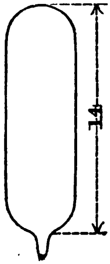
Cylinder M. Diameter 3·08 inches.
Length 14 inches.

In parts of an inch.

$$\text{Thicknesses measured}\left\{\begin{matrix}0\cdot0320\\0\cdot0324\\0\cdot052\\0\cdot0316\\0\cdot0326\\0\cdot0322\end{matrix}\right\}\begin{matrix}\text{Minimum}\\=0\cdot032\text{ inch.}\end{matrix}$$

Collapsing pressure = 103 lbs. per square inch.

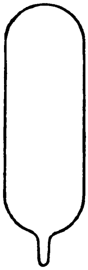
Fig. 15.



EXPERIMENT 13.

Cylinder N. Diameter 3·25 inches.
Length 14 inches.

Fig. 16.



In parts of an inch.

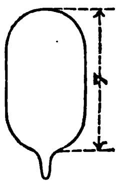
$$\text{Thicknesses measured}\left\{\begin{array}{l}0{\cdot}0452\\0{\cdot}0436\\0{\cdot}0472\\0{\cdot}0422\\0{\cdot}0426\\0{\cdot}0436\\0{\cdot}0452\end{array}\right\}\text{Minimum}=0{\cdot}042\text{ inch.}$$

Collapsing pressure = 175 lbs. per square inch.

EXPERIMENT 14.

Cylinder O. Diameter 4·05 inches.
Length 7·0 inches.

Fig. 17.



In parts of an inch.

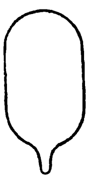
$$\text{Thicknesses measured}\left\{\begin{array}{l}0{\cdot}0454\\0{\cdot}0384\\0{\cdot}0368\\0{\cdot}0344\\0{\cdot}0348\\0{\cdot}0392\\0{\cdot}0348\end{array}\right\}\text{Minimum}=0{\cdot}034\text{ inch.}$$

Collapsing pressure = 202 lbs. per square inch.

EXPERIMENT 15.

Cylinder P. Diameter 4·05 inches.
Length 7 inches.

Fig. 18.



In parts of an inch.

$$\text{Thicknesses measured}\left\{\begin{array}{l}0{\cdot}0502\\0{\cdot}0464\\0{\cdot}0460\\0{\cdot}0464\\0{\cdot}0510\\0{\cdot}0498\\0{\cdot}0558\end{array}\right\}\text{Minimum}=0{\cdot}046\text{ inch.}$$

Collapsing pressure = 380 lbs. per square inch.

Experiment 16.

Cylinder Q. Diameter 4·06 inches.
Length 13·8 inches.

In parts of an inch.

$$\text{Thicknesses measured}\left\{\begin{array}{l}0{\cdot}0448\\0{\cdot}050\\0{\cdot}0474\\0{\cdot}0490\\0{\cdot}0476\\0{\cdot}0470\\0{\cdot}053\\0{\cdot}0434\end{array}\right\}\begin{array}{l}\text{Minimum}\\ \quad =0{\cdot}043 \text{ inch.}\end{array}$$

Collapsing pressure = 180 lbs. per square inch.

Fig. 19.

Experiment 17.

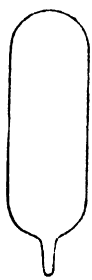
Cylinder R. Diameter 4·02 inches.
Length 13·8 inches.

In parts of an inch.

$$\text{Thicknesses measured}\left\{\begin{array}{l}0{\cdot}0678\\0{\cdot}0664\\0{\cdot}0728\\0{\cdot}0718\\0{\cdot}0660\\0{\cdot}0644\\0{\cdot}0706\\0{\cdot}0682\end{array}\right\}\begin{array}{l}\text{Minimum}\\ \quad =0{\cdot}064 \text{ inch.}\end{array}$$

Collapsing pressure = 297 lbs. per square inch.

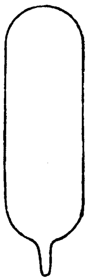
Fig. 20.



EXPERIMENT 18.

Cylinder S. Diameter 3·98 inches.
Length 14·0 inches.

Fig. 21.



In parts of an inch.

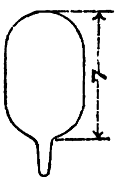
$$\begin{array}{r}\text{Thicknesses}\\\text{measured}\end{array}\left\{\begin{array}{l}0\cdot0792\\0\cdot0774\\0\cdot0762\\0\cdot0812\\0\cdot0828\\0\cdot0848\\0\cdot0836\\0\cdot0778\\0\cdot0766\end{array}\right\}\text{Minimum}=0\cdot076\text{ inch.}$$

Collapsing pressure = 382 lbs. per square inch.

EXPERIMENT 19.

Cylinder T. Diameter 4·05 inches.
Length 7·0 inches.

Fig. 22.



In parts of an inch.

$$\begin{array}{r}\text{Thicknesses}\\\text{measured}\end{array}\left\{\begin{array}{l}0\cdot079\\0\cdot081\\0\cdot090\\0\cdot086\\0\cdot086\\0\cdot079\\0\cdot086\end{array}\right\}\text{Minimum}=0\cdot079\text{ inch.}$$

This cylinder remained unbroken after sustaining a pressure of 500 lbs. per square inch.

Experiment 20*.

Cylinder V. Diameter 4·2 inches.
Length 22 inches.

	In parts of an inch.	
Thicknesses measured	0·063	Minimum = 0·055 inch.
	0·056	
	0·057	
	0·055	
	0·057	
	0·055	
	0·056	

Collapsed with 120 lbs. per square inch.

Experiment 21*.

Cylinder W. Diameter 4·1 inches.
Length 21·5 inches.

	In parts of an inch.	
Thicknesses measured	0·0535	Minimum = 0·051 inch.
	0·051	
	0·055	
	0·052	
	0·053	
	0·060	
	0·057	
	0·0525	
	0·055	

Collapsed with 129 lbs. pressure per square inch.

* The experiments marked with an asterisk were not originally included in the calculations; but the results are strictly in conformity with those previously reduced.

EXPERIMENT 22*.

Cylinder X. Diameter 4·2 and 4·1 inches.
Length 22 inches.

In parts of an inch.

Thicknesses measured $\left\{\begin{array}{l} 0{\cdot}0455 \\ 0{\cdot}047 \\ 0{\cdot}047 \\ 0{\cdot}049 \\ 0{\cdot}047 \\ 0{\cdot}047 \\ 0{\cdot}052 \\ 0{\cdot}047 \\ 0{\cdot}049 \\ 0{\cdot}047 \\ 0{\cdot}054 \\ 0{\cdot}046 \end{array}\right\}$ Minimum = 0·0455 inch.

Collapsing pressure = 125 lbs. per square inch.

Green Glass.

EXPERIMENT 23.

Globe Z. Diameters 5·0 and 5·02 inches.

In parts of an inch.

Thicknesses measured $\left\{\begin{array}{l} 0{\cdot}015 \\ 0{\cdot}013 \\ 0{\cdot}0125 \\ 0{\cdot}019 \\ 0{\cdot}016 \\ 0{\cdot}018 \\ 0{\cdot}021 \\ 0{\cdot}0126 \\ 0{\cdot}013 \end{array}\right\}$ Minimum = 0·0125 inch.

Collapsed with 212 lbs. per square inch.

TABLE VII. — *Summary of the Results of Experiments on the Resistance of Glass Globes to an External Pressure.*

Number of Experiment.	Description of Glass.	Diameters, in inches.	Minimum Thickness, in inches.	Collapsing Pressure per square inch, in lbs.
I.	Flint-glass . . .	5·05 and 4·76	0·014	292
II.		5·08 and 4·7	0·018	410
III.		4·95 and 4·72	0·022	470
IV.		5 6	0 020	475
V.		8·22 and 7·45	0·010	35
VI.		8·2 and 7·2	0·012	42
VII.		8·2 and 7·4	0·015	60
VIII.		4·0 and 3·98	0·024	(900)*
IX.		4·0	0·025	(900)*
X.		6·0	0·059	(1000)*
XXIII.	Green glass . .	5·0 and 5·02	0·0125	212

TABLE VIII.—*Summary of Results of Experiments on the Resistance of Glass Cylinders to an External Force.*

Number of Experiment.	Description of Glass.	Diameters, in inches.	Length, in inches.	Minimum Thickness, in inches.	Collapsing Pressure, per square inch, in lbs.
XI.	Flint-glass . .	3·09	14·0	0·024	85
XII.		3·08	14·0	0·032	103
XIII.		3·25	14·0	0·042	175
XIV.		4·05	7·0	0·034	202
XV.		4·05	7·0	0·046	380
XVI.		4·06	13·8	0·043	180
XVII.		4·02	13·8	0·064	297
XVIII.		3·98	14·0	0·076	382
XIX.		4·05	7·0	0·079	(500)†
XX.		4·20	22·0	0·055	120
XXI.		4·10	21·5	0·051	129
XXII.		4·15	22·0	0·046	125

* These globes remained unbroken. † Remained unbroken.

SECTION V.

REDUCTION OF THE PRECEDING RESULTS.

I. *Generalisation of the Results of Experiments on the Resistance of Glass Globes and Cylinders to External Pressure.*

Let us assume—

$P=$ the external pressure in pounds per square inch to produce rupture.

$D=$ the diameter of the globe or tube, as the case may be, in inches.

$k=$ the thickness of the glass in inches.

$p=$ the pressure P reduced to unity of thickness, viz. $k=\cdot01$ inch.

C, a, β, constants to be determined from the data supplied by the experiments.

Then for the globes we assume

$$P=\frac{Ck^{a}}{D^{\beta}}, \quad . \quad . \quad . \quad . \quad (1)$$

and for the cylinders

$$P=\frac{C'k^{a}}{D^{\beta'}L^{a'}}, \quad . \quad . \quad . \quad (2)$$

where the exponent of the thickness is the same in both formulæ.

Hence we find for globes of the same diameter and also for cylinders of the same length and diameter—

$$a=\frac{\log P_1-\log P_2}{\log k_1-\log k_2} \quad . \quad . \quad (3)$$

Taking the results of Experiments 1 and 2, we find $a=1\cdot35$; from 5 and 6 we find $a=1\cdot33$; from 11 and 12 we find $a=1\cdot28$; from 16 and 17 we find $a=1\cdot26$;

and from 15 and 16 we find $a=2$. Hence we get for the mean value of a,

$$a=\tfrac{1}{5}\{1{\cdot}35+1{\cdot}33+1{\cdot}28+1{\cdot}26+2\}=1{\cdot}4.$$

Again, the following formula enables us to reduce the pressure P, of the cylinders as well as of the globes, to unity of thickness,

$$\log p=\log \mathrm{P}-a\log(100\,k) \quad . \quad . \quad (4)$$

Making these calculations, we obtain the following Tables of results:--

TABLE IX.—*Reduction of the Results of Experiments on the Resistance of Glass Globes to Unity of Thickness.*

Number of Experiment.	D. Diameter, in inches.	k. Thickness, in inches.	P. Collapsing Pressure, in lbs. per square inch.	p. P reduced to Unity of Thickness.
I.	5·05	·014	292	178
II.	5·08	·018	410	168
III.	4·95	·022	470	156
IV.	5·60	·020	475	180
V.	8·22	·010	35	35
VI.	8·20	·012	42	32·54
VII.	8·20	·015	60	34·01

TABLE X.—*Reduction of the Results of Experiments on the Resistance of Glass Cylinders to Unity of Thickness.*

Number of experiment.	D. Diameter, in inches.	L. Length, in inches.	k. Thickness, in inches.	P. Collapsing Pressure, in lbs. per square inch.	p. P reduced to Unity of Thickness.
XI.	3·09	14	0·024	85	27·36
XII.	3·08	14	0·032	103	20·23
XIII.	3·25	14	0·042	175	23·47
XIV.	4·05	7	0·034	202	36·41
XV.	4·05	7	0·046	380	44·86
XVI.	4·06	13·8	0·043	180	23·36
XVII.	4·02	13·8	0·064	297	22·10
XVIII.	3·98	14	0·076	382	22·33

Let D_1, p_1 be put for the data derived from Experiment 1; D_2, p_2 for the data derived from Experiment 2, and so on; then we get from equation (1),

$$\beta=\frac{\log p_1+\log p_2+\log p_3-(\log p_5+\log p_6+\log p_7)}{\log D_5+\log D_6+\log D_7-(\log D_1+\log D_2+\log D_3)} \quad . \quad . \quad (5)$$

$$\beta=\frac{\log p_1-\log p_7}{\log D_7-\log D_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

$$\beta=\frac{\log p_2+\log p_3+\log p_4-(\log p_5+\log p_6+\log p_7)}{\log D_5+\log D_6+\log D_7-(\log D_2+\log D_3+\log D_4)} \quad . \quad . \quad (7)$$

From equation (5) we find $\beta=3{\cdot}43$; from equation (6) we find $\beta=3{\cdot}25$; and from equation (7) we find $\beta=3{\cdot}56$; and the mean of these values gives

$$\beta=\tfrac{1}{3}(3{\cdot}43+3{\cdot}25+3{\cdot}56)=3{\cdot}4.$$

For the value of the constant C, we find

$$\log C=\tfrac{1}{7}(\log p_1+\ldots\ldots+\log p_7)+ \frac{\beta}{7}(\log D_1+\ldots\ldots+\log D_7)+2a, \quad . \quad (8)$$

whence we find $C=28{,}300{,}000$.

Substituting the values of a, β, C thus obtained in the general formula (1), we get

$$P=28{,}300{,}000\times\frac{k^{1\cdot 4}}{D^{3\cdot 4}} \quad . \quad . \quad (9)$$

which is the general formula for calculating the strength of flint-glass globes subjected to external pressure. In order to facilitate calculation, this formula may be written

$$\log P=4{\cdot}6518+1{\cdot}4\log(100\,k)-3{\cdot}4\log D \quad . \quad (10)$$

Calculating the value of P by this formula from the data of Experiment 23, viz. $D=5$ and $k={\cdot}0125$, we find

$$\log P=4{\cdot}6518+1{\cdot}4\log 1{\cdot}25-3{\cdot}4\log 5=\log 258,$$

that is $P=258$ lbs. Now this would be the crushing

pressure supposing the globe to be flint-glass; but the crushing pressure given by the experiment is 212 lbs.; hence it appears that the resistance of green glass to external pressure differs very little from that of flint-glass. The following Table will show how nearly formula (9) represents the results of the experiments on glass globes.

TABLE XI.—*Results of Experiments on the Resistance of Glass Globes to External Pressure.*

Number of Experiment.	D.	k.	P by Experiment.	P by Formula (9).	Proportional Error by Formula.
I.	5·05	·014	292	292	0
II.	5·08	·018	410	408	$-\frac{1}{100}$
III.	4·95	·022	470	580	$+\frac{1}{4}$
IV.	5·6	·020	475	340	$-\frac{1}{4}$
V.	8·22	·010	35	35	0
VI.	8·2	·012	42	44·8	$+\frac{1}{20}$
VII.	8·2	·015	60	61·3	$+\frac{1}{50}$
VIII.	4·0	·024	900*	1370	
IX.	4·0	·025	900*	1450	
X.	6·0	·059	1000*	1218	
XXIII.	5·02	·0125	212†	258	$+\frac{1}{5}$

The lengths of the cylinders of Experiments 11, 12, and 13 are the same, and their diameters are nearly equal to one another. The same observation applies to the cylinders of Experiments 14 and 15, and also to Experiments 16 and 71. In order, therefore, to reduce the pressures p to uniformity of diameter, we may assume, for such small differences, that D varies as $\frac{1}{P}$. These reductions being made, we may obtain the following Table:—

* Remained unbroken. † Green glass.

TABLE XII.—*Reduction of the Results of Experiments on Glass Cylinders to uniformity of Diameter, &c.*

Number of Experiment.	D. Diameter, in inches.	L. Length, in inches.	p. P reduced to Unity of Thickness.	p D L.
11, 12, 13,	3	14	24·81	1042
14, 15,	4·05	7	40·63	1151
16, 17,	4·05	13·8	22·67	1260
18.	3·98	14	22·33	1240

Mean value of p L D $= \frac{4)4693}{1173}$

Here the continued product of the pressure, diameter, and length is shown to be very nearly a constant quantity, the thickness of the glass being the same, that is for $k = \cdot 01$. Hence we have

$$C = \frac{pDL}{\cdot 01^a} \quad . \quad . \quad . \quad . \quad (11)$$

Now the mean value of pDL is 1173, as shown in Table XII, and $a = 1 \cdot 4$, as determined by equation (3); hence we find

$$C = \frac{1173}{\cdot 01^{1 \cdot 4}} = 740{,}000.$$

Substituting these values of the constants in equation (2), we get

$$P = 740{,}000 \frac{k^{1.4}}{DL}, \quad . \quad . \quad . \quad (12)$$

which is the general formula for calculating the strength of glass cylinders subjected to external pressure, within the limits indicated by the experiments, that is, provided their length is not less than twice their diameter, and not greater probably than six times their diameter. This law

of strength is precisely similar to that found for sheet-iron tubes.

For convenience of calculation, this formula may be written

$$\log P = 3{\cdot}06923 + 1{\cdot}4 \log (100\,k) - \log (DL) \quad . \quad (13)$$

The following Table will show how nearly formula (12) represents the results of the experiments on glass cylinders :—

TABLE XIII.—*Results of Experiments on the Resistance of Glass Cylinders to External Pressure.*

Number of Experiment.	D.	L.	k.	P by Experiment.	P by Formula.	Proportional Error by Formula.
XI.	3·09	14	·024	85	86	$+\frac{1}{80}$
XII.	3·08	14	·032	103	138	$+\frac{1}{3}$
XIII.	3·25	14	·042	175	192	$+\frac{1}{9}$
XIV.	4·05	7	·034	202	227	$+\frac{1}{10}$
XV.	4·05	7	·046	380	351	$-\frac{1}{13}$
XVI.	4·06	13·8	·043	180	161	$-\frac{1}{9}$
XVII.	4·02	13·8	·064	297	284	$-\frac{1}{20}$
XVIII.	3·98	14	·076	382	361	$-\frac{1}{18}$
XIX.	4·05	7	·079	500	747	Unbroken.
XX.	4·2	22	·055	120	138	$+\frac{1}{7}$
XXI.	4·1	21·5	·051	129	130	$+\frac{1}{129}$
XXII.	4·2	22	·0455	125	107	$-\frac{1}{7}$

Comparative Strength of Glass and Sheet-iron Cylinders subjected to an External Pressure tending to produce Collapse.

The formula of strength for sheet-iron cylinders, after reducing L to inches, is

$$P' = 806{,}300 \times 12 \times \frac{k^{2\cdot19}}{LD}.$$

Now for cylinders of the same diameter, length, and

thickness, we find, by dividing equation (12) by the above,

$$\frac{P}{P'}=\frac{\cdot 0764}{k^{\cdot 79}} \quad . \quad . \quad . \quad . \quad (14)$$

When $k=\cdot 043$, as in most of the experiments on iron, then $\frac{P}{P'}=\frac{11}{12}$; that is, in this case, the strengths of the two cylinders will be nearly equal to one another.

II. *Generalisation of the Results of the Experiments on the Resistance of Glass Globes, Cylinders, and Ellipsoids to Internal Pressure.*

Let D = the diameter of the globe or cylinder, as the case may be.

k = the thickness of the material in inches.

a = the longitudinal sectional area of the material in square inches; that is, in the direction of the line of rupture, or line of minimum strength.

A = the longitudinal section in square inches.

P = the bursting pressure in lbs. per square inch.

T = the tenacity of the material in lbs. per square inch.

Then we find

$$P=\frac{aT}{A}; \quad . \quad . \quad . \quad . \quad (15)$$

$$\therefore \quad T=\frac{PA}{a}; \quad . \quad . \quad . \quad . \quad (16)$$

that is, $\frac{PA}{a}$ is a constant for vessels of the same material. This theoretical deduction is fully confirmed by the results of these experiments, as arranged in the following Table:—

TABLE XIV.—*Resistance of Glass Globes, Cylinders, and Ellipsoids to an Internal Pressure.*

Number of Experiment.	Description of Glass.	D.	k.	P.	Value of $P\frac{A}{a}$.	Mean Value of $P\frac{A}{a}$.
1.	Flint-glass	4·0 and 3·98	·024	84	3500	4200
2.		4·0 and 3·98	·025	93	3710	
3.		4·0	·038	150	3950	
4.		4·5 and 4·55	·056	280	5650	
5.		5·1 and 5·12	·058	184	4050	
6.		6·0	·059	152	3870	
7.		4·05 and 7·0	·079	282	4660	
8.	Green glass	4·95 and 5·0	·022	90	4040	4800
9.		4·95 and 5·0	·020	85	5280	
10.		4·0 and 4·05	·018	84	4690	
11.		4·0 and 4·03	·016	82	5150	
12.	Crown-glass	4·2 and 4·35	·025	120	5120	6000
13.		4·2 and 4·05	·021	126	6190	
14.		5·9 and 5·8	·016	69	6300	
15.		6·0 and 6·3	·020	86	5290	
16.		4·1 and 7·0	·016	80	6360	
17.		4·0 and 7·0	·019	109	6900	

Hence we have the tenacity of glass,—

lbs. per sq. in.

$T = 4200$, for flint-glass,

$T = 4800$, for green glass,

and $T = 6000$, for crown-glass.

The general equation (15), giving the bursting pressure in pounds per square inch, then becomes—

$$P = 4200 \times \frac{a}{A}, \text{ for flint-glass,}$$

$$P = 4800 \times \frac{a}{A}, \text{ for green glass.}$$

$$P = 6000 \times \frac{a}{A}, \text{ for crown-glass.}$$

For globes of uniform diameter and thickness these formulæ become—

$$P = 16{,}800 \times \frac{k}{D}, \text{ for flint-glass,}$$

$$P = 19{,}200 \times \frac{k}{D}, \text{ for green glass,}$$

$$P = 24{,}000 \times \frac{k}{D}, \text{ for crown-glass.}$$

III. *Generalisation of the Results of Experiments on the Tensile and Compressive Resistances of Glass.*

Mean tenacity (T_1) of glass in the form of bars $= \frac{1}{4}(2286 + 2540 + 2890 + 2540) = 2560$ lbs. per sq. in.;

Mean tenacity (T'_1) of glass in the form of thin plates $= \frac{1}{3}(4200 + 4800 + 6000) = 5000$ lbs. per square inch;

$$\therefore \quad \frac{T'_1}{T_1} = \frac{5000}{2560} = 2 \text{ nearly,}$$

that is, the tenacity of glass in the form of thin plates is about twice that of glass in the form of bars.

Mean resistance (T_2) of glass to compression

$= \frac{1}{3}(27582 + 31876 + 31003) = 30{,}150$ lbs. per sq. in.;

$$\therefore \quad \frac{T_2}{T_1} = \frac{30{,}150}{2560} = 11{\cdot}8 \text{ nearly,}$$

that is, the ultimate resistance of glass to a crushing force is about twelve times its resistance to extension.

IV. *Resistance of Rectangular Glass Bars to a Transverse Strain.*

Let l = the length of the bar supported at the ends and loaded in the middle.

W = breaking weight in lbs.

K = area of the whole transverse section.

D = the whole depth of the section.

d, d_1 = the respective distances of the top and bottom edges from the neutral axis.

T_1 = the tensile resistance of the material in lbs. per square inch.

T_2 = the compressive resistance of the material in lbs. per square inch.

Then we have TATE'S "Strength of materials," equations (27) and (6)—

$$W = \tfrac{4}{3}.\frac{T_1 d_1 K}{l}, \text{ and } \frac{T_1}{T_2} = \frac{d}{d_1};$$

hence we get

$$W = \tfrac{4}{3}.\frac{T_1.T_2}{T_1 + T_2} \times \frac{K.D}{l} = C\,\frac{KD}{l}, \qquad . \quad (17)$$

where the constant

$$C = \tfrac{4}{3}.\frac{T_1.T_2}{T_1 + T_2} = \tfrac{4}{3} \times \frac{2560 \times 30150}{32710} = 3140 \text{ nearly.}$$

Substituting this value of the constant, equation (16) becomes

$$W = 3140\,\frac{KD}{l}, \qquad . \quad . \quad . \quad . \quad . \quad (18)$$

which expresses the transverse strength of a rectangular bar of glass supported at the ends and loaded in the middle.

III.

RESEARCHES ON THE TENSILE STRENGTH OF WROUGHT IRON AT VARIOUS TEMPERATURES.

(From the Report of the British Association for 1856.)

On a previous occasion I had the honour of conducting, for the Association, a series of experiments to determine the effects of temperature on the strength of cast iron. In that inquiry I endeavoured to show to what extent the cohesion of that material was affected by change of temperature, and taking into account the rapidity with which iron imbibes caloric, and the facility with which it parts with it, it is equally interesting to know to what extent wrought iron is improved or deteriorated by similar changes. In the present inquiry, as in the former on cast iron, the expansion of the metal by heat is not the question for solution. Rondelet, Smeaton, and others, have already investigated that subject, and it now only remains for us to determine the effects produced on the strength of malleable iron by changes of temperature varying from —30° of Fahrenheit to a red heat, perceptible in daylight.

The immense number of purposes to which iron is applied, and the changes of temperature to which it is exposed, render the present inquiry not only interesting, but absolutely essential to a knowledge of its security under the varied influences of those changes; and when it is known that most of our iron constructions are exposed to a range of temperature varying from the extreme cold of winter to the intense heat of summer, it is assuredly de-

sirable to ascertain the effects produced by these causes on a material from which we derive so many advantages, and on the security of which the safety of the public not unfrequently depends.

Independent of atmospheric influences, another consideration presents itself in reference to the durability and ultimate stability of iron under changes much greater than those alluded to above, and this is the strength of such vessels as pans and boilers subjected to the extreme temperatures of boiling liquids on one side, and the intense heat of a furnace on the other. But even these extremes, however great, do not seem seriously to affect the cohesive strength of wrought-iron plates, nor do they appear to cause any disruption of the laminated structure which results from the system of piling and rolling adopted in the manufacture, excepting only where small particles of scoria happen to intervene between the laminated surfaces. These not unfrequently prevent a perfect welding, as the plate is compressed by passing through the rolls, and the effects of temperature are strikingly exhibited in the production of large blisters upon the surface of the plate, as shown in the annexed sketch at *a*, *a*. Now the reason of

Fig. 23.

this is the want of solidity and homogeneity in the plate, and the consequent expansion of the lower part exposed to the greatest heat. Let us suppose, for the sake of illustration, the plate to be $\frac{3}{8}$ths of an inch thick, and the surface *b* to be the interior of a boiler-plate, and the surface *a*, *a* to be exposed to the action of the fire in the furnace. In this case it is evident that the temperature

of the side *a*, *a* may be upwards of 1000°, while that of *b* is very little above 212°, or the temperature of boiling water; and supposing there be any imperfection or want of soundness in the plate, the result will be a greater expansion on the exterior surface, causing it to rise up in blisters in the manner we have described. These defects are invariably present when the plates are not sound; but in other respects, where the bars which form the pile are clear and free from rust or scoria, and are well welded in the rolling process, the wide difference between the temperature of one side and that of the other produces, apparently, no injurious effect on the strength of the plate. It is, however, widely different when the whole of the plates are exposed to the same degree of temperature, as in this position the strengths are increased or diminished according as the temperature approaches or recedes from the point where the strength is a maximum.

In order to show how the results were obtained, it will be necessary to describe the apparatus and mode of conducting the experiments.

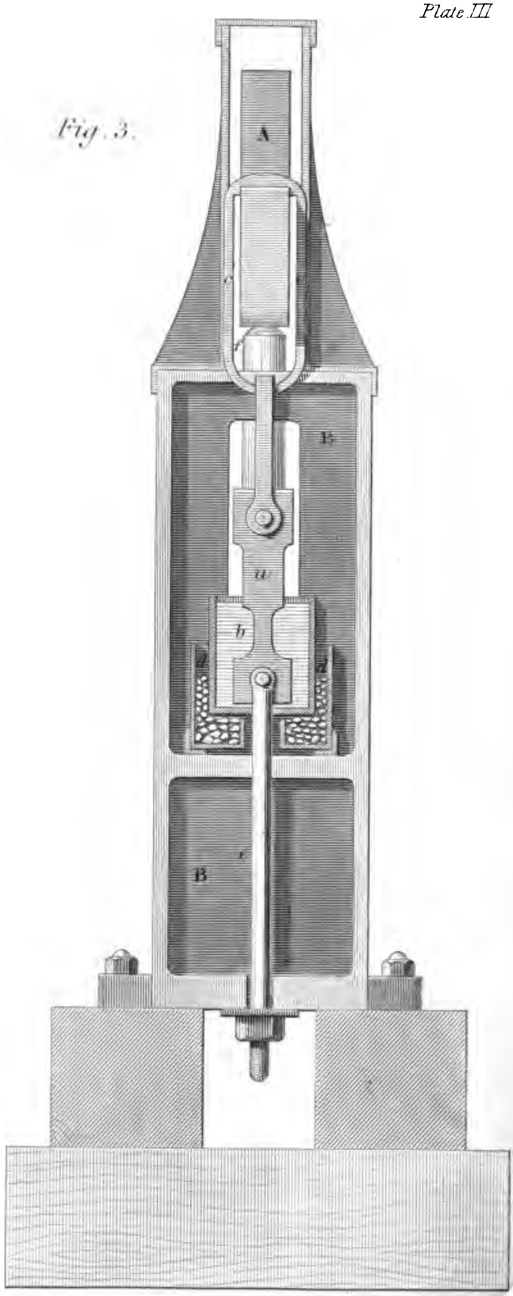
The apparatus consisted of a powerful wrought-iron lever, Plate III. A, *figs.* 2 and 3, capable of imparting a force of more than 100,000 lbs., or 45 tons per square inch to the specimen to be broken. The lever is supported in a cast-iron standard or frame B, arranged for the reception of specimens of the material to be subjected to a crushing force or tensile strain. On the short arm of the lever the plates and bars (one of which is seen at *a*) were suspended by a shackle *e*, and held down to the bottom of the cast-iron standard by the rod and screw *e*; on this rod the box, *b*, was fixed, and prepared to hold a bath of oil or water, in which the iron to be broken was immersed. Below this box was a fire-grate, *d*, for heating the liquid in the bath to the required temperature, and this grate could be drawn backwards from the box, *b*, when the required tem-

IMENTS

NGTH OF IRON.

Plate III

Fig. 3.



perature was attained or when it became too high. The fulcrum of the lever is shown at *f*, and the scale in which the weights were placed at *g*. The cast-iron standard was firmly bolted to the heavy balks of timber upon which it stands, and the pressure on the specimen was adjusted by placing weights in the scale.

The plates experimented upon were of the form shown in fig. 24, reduced at *a*, to $2\frac{1}{2}$ inches wide, and at *b* to 2 inches wide, in order to secure fracture at the part of the

Fig. 24.

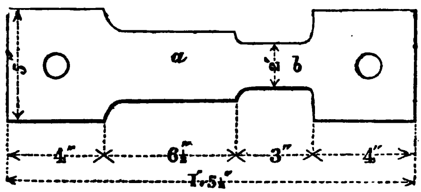


Fig. 25.

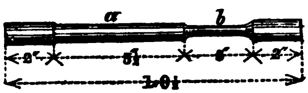


plate immersed in the liquid in the bath. At each end two holes are drilled to receive the bolts which fixed them in the shackles. The wrought-iron bars were formed in a similar manner. They were $\frac{7}{8}$ inch in diameter, reduced to $\frac{3}{4}$ of an inch at *a*, and to $\frac{9}{16}$ inch, or $\frac{1}{2}$ inch at *b*. The shackles were made to clasp the bars below the shoulders so as to apply the strain requisite to cause fracture. It is evident that the weakest part of the bars being within the bath, breakage was sure to occur at that point where the temperature was raised or lowered to the required degree.

With these preparations, the experiments proceeded as follows: — the bar to be broken was fixed between the shackles of the lever; and, if necessary, the bath was filled, and the fire drawn close under it; as soon as the intended temperature was attained, the lever was let down by the crab, and weights carefully added to the scale until the bar broke. During the process the temperature was observed from time to time, and the fire adjusted accordingly, and the temperature registered in the Tables was observed immediately after the bar had given way.

Experiments to ascertain the Influence of Temperature on the Tensile Strength of Boiler Plate.

TABLE I.—Strain applied in the direction of the fibre. Boiler plate; sectional area $= 2{\cdot}02 \times {\cdot}34 = {\cdot}6868$ sq. in.

Temperature, Fahr.	No. of experiments.	Strain applied in lbs.	Elongation in inches.	Breaking weight per square inch in lbs.	Remarks.
0°	1	18,540			For figures of the specimens
	2	26,940			experimented on, see
	3	27,780			Plate IV., the numbering
	4	28,620			of the figures corres-
	5	29,460			ponding with that of the
	6	30,300			tables.
	7	31,140			Broke with a clear ringing
	8	31,980			noise, almost like cast-
	9	32,820			iron.
	10	33,660	·14	49,009	=21·879 tons.

The temperature in this experiment was reduced to zero by a mixture of pounded ice and salt, carefully placed round the plate in order to secure the same temperature in the metal as in the bath.

TABLE II.—Strain applied across the fibre.

Boiler plate; sectional area $=2 \cdot 5 \times \cdot 313 = \cdot 7825$ sq. in.

Temperature, Fahr.	No. of experiments.	Strain applied in lbs.	Elongation in inches.	Breaking weight per square inch in lbs.	Remarks.
60°	1	8,190			
	2	10,140			
	3	16,860			
	4	23,580			
	5	30,300			
	6	31,980	·162	40,357	= 18·001 tons.

The experiments in the above and No. III. Table were conducted at the temperature of the atmosphere. Both specimens indicated a hard brittle iron, the interior laminations having somewhat the appearance of cast iron, with a fracture widely different from that exhibited when torn asunder in the direction of the fibre.

TABLE III.—Strain applied across the fibre.

Boiler plate; sectional area $=2 \cdot 0 \times \cdot 32 = \cdot 64$ sq. in.

Temperature, Fahr.	No. of experiments.	Strain applied in lbs.	Elongation in inches.	Breaking weight per square inch. in lbs.	Remarks.
60°	1	10,140 (1680 lbs. were added at a time till weight =)			Some steely spots in fracture.
	10	25,260			
	11	26,100			
	12	26,940			
	13	27,780	·1	43,406	= 19·377 tons.

TABLE IV.—Strain applied in the direction of the fibre. Boiler plate; sectional area $=1\cdot99\times\cdot32=\cdot6368$ sq. in.

Temperature, Fahr.	No. of experiments.	Strain applied in lbs.	Elongation in inches.	Breaking weight per square inch in lbs.	Remarks.
60°	1	10,140			
	2	18,540			
	3	20,220			
	4	21,900			
	5	23,580			A fissure containing cinder extended one-third of the breadth of the plate. In some parts the blade of a penknife could be introduced.
	6	25,260			
	7	26,100			
	8	26,940			
	9	27,780			
	10	28,620			
	11	29,460			
	12	30,300			
	13	31,140			
	14	31,980	·2	50,219	=22·414 tons.

In some former experiments on the tensile strength of wrought-iron plates *, the strength of the specimens was rather more uniform, and there appeared to be no difference between the strength of the plates when torn asunder in the direction of the fibre, and the strength when the strain was applied across it. Comparing Tables II. and III. with IV., we find the breaking weight in the direction of the fibre is to that across it as 22·41 : 18·67, or as 5 : 4 nearly; but it is possible that this arises from inequality in the rolling of the two specimens.

* Philosophical Transactions for 1850, p. 677, the results of which are also given in "Useful Information," First Series, Appendix I.

TABLE V.—Strain applied across the fibre.

Boiler plate; sectional area $=1 \cdot 99 \times \cdot 33$ sq. inch.

Temperature, Fahr.	No. of experiments.	Strain applied in lbs.	Elongation in inches.	Breaking weight per square inch in lbs.	Remarks.
110°	1	25,260			
	2	26,940			Fracture very uneven.
	3	27,780			
	4	28,620			
	5	29,460	·13	44,160	=19·714 tons. The last weight was hardly on: 29,000 lbs. was probably nearer the breaking weight.

TABLE VI.—Strain applied in the direction of the fibre.

Boiler plate; sectional area $=2 \cdot 0 \times \cdot 34 = \cdot 68$ sq. inch.

Temperature, Fahr.	No. of experiments.	Strain applied in lbs.	Elongation in inches.	Breaking weight per square inch in lbs.	Remarks.
112°	1	18,540			
	2	20,220			
	3	21,900			
	4	23,580			
	5	25,260			
	6	26,940			
	7	28,620		42,088	=18·789 tons.

Table VII.—Strain applied in the direction of the fibre. Boiler plate; sectional area $=2·54 \times ·32 = ·8128$ sq. inch.

Temperature, Fahr.	No. of experiments.	Strain applied in lbs.	Elongation in inches.	Breaking weight per square inch in lbs.	Remarks.
120°	1	25,260			
	2	26,940			
	3	28,620			
	4	30,300			
	5	31,140			
	6	31,980			
	7	32,400			
	8	33,660			
	9	34,500			
	10	35,340			
	11	35,760			
	12	36,180			
	13	36,600			
	14	37,020	·173	40,625	=18·136 tons.

The last three experiments, at a mean temperature of 114°, indicate a near approach to uniformity of strength, that broken across the fibre being the strongest; the very reverse of those fractured at 60°, the numbers being as 197 : 184, or as 44 : 41 nearly, showing a loss of about ·007 per cent. It is difficult to account for these changes and defects in the strengths of the plates, as most of the specimens were cut from one plate, and all of them were of the same manufacture.

Table VIII.—Strain applied in the direction of the fibre. Boiler plate; sectional area $=2·6 \times ·308 = ·8008$ sq. inch.

Temperature, Fahr.	No. of experiments.	Strain applied in lbs.	Elongation in inches.	Breaking weight per square inch in lbs.	Remarks.
212°	1	30,300			
	2	31,980	·15	39,935	=17·828 tons.

Broken in boiling water. This specimen did not break at the narrowest part of its section, which shows a serious defect in the plate.

TABLE IX.—Strain applied across the fibre.

Boiler plate; sectional area $=2\cdot01 \times \cdot33 = \cdot6633$ sq. inch.

Temperature, Fahr.	No. of experiments.	Strain applied in lbs.	Elongation in inches.	Breaking weight per square inch in lbs.	Remarks.
212°	1	18.540			Broken in boiling water.
	2	20,220			
	3	21,900			
	4	23,580			
	5	25,260			
	6	26.940			
	7	27,780			
	8	28,620			
	9	29,460			
	10	30,300	·11	45,680	=20·392 tons.

In Table VIII., where the specimen was drawn in the direction of the fibre, there appears to be some defect in the plate, as it gave way, not at the smallest section, but at a wider part of the plate, with a force of only 39,935 lbs. to the square inch, whereas the same plate torn asunder across the fibre sustained a force of 45,680 lbs. before breaking. This difference of strength can only be accounted for by some defect not perceptible when the fracture was examined. The difference of strength, at the temperature of boiling water, indicated by these two specimens, is as 178 : 203, or in the ratio of ·87 : 1.

TABLE X.—Strain applied in the direction of the fibre.
Boiler plate; sectional area $=2\cdot0 \times \cdot34 = \cdot68$ sq. inch.

Temperature, Fahr.	No. of experiments.	Strain applied in lbs.	Elongation in inches.	Breaking weight per square inch in lbs.	Remarks.
212°	1	18,540			Broken in boiling water.
	2	20,220			
	3	21,900			
	4	23,580			
	5	25,260			
	6	26,940			
	7	27,780			
	8	28,620			
	9	29,460			
	10	30,300			
	11	31,140			
	12	31,980			
	13	32,820			
	14	33,660	·22	49,500	=22·098 tons.

Comparing this plate with that in experiment VIII., it will be seen that the power of resistance of the former is more than one fifth greater than that of the latter, showing that there must have been some defect in the longer section of the specimen, or fracture would not have ensued at so early a period of the experiment. We cannot abandon this experiment, as no defect presented itself, if we except the highly crystallised state of the fracture, both specimens having been drawn asunder in the direction of the fibre. In these experiments it will be observed that the infusion of heat into wrought-iron plates, from zero to 212°, does not injure, but rather improves, their tensile strength.

TABLE XI.—Strain applied in the direction of the fibre. Boiler plate; sectional area $=2{\cdot}01 \times {\cdot}32 = {\cdot}6432$ sq. inch.

Temperature, Fahr.	No. of experiments.	Strain applied in lbs.	Elongation in inches.	Breaking weight per square inch in lbs.	Remarks.
270°	1	18,540			Broken in hot oil.
	2	20,220			
	3	21,900			
	4	23,580			Broke before the last
	5	25,260			weight was fairly
	6	26,940			on; 28,320 lbs. pro-
	7	27,780			bably nearer.
	8	28,620	·13	44,020	=19·651 tons.

From this experiment it appears that an increase of 58° of heat makes no perceptible difference in the strength of the plate. If we take the mean of the two previous experiments, in the direction of the fibre, it will be found there is no great difference between them, the mean of Tables VIII. and X. being 44,708, and Table XI. giving 44,020 lbs. to the square inch.

TABLE XII.—Strain applied in the direction of the fibre. Boiler plate; sectional area $=2{\cdot}0 \times {\cdot}32 = {\cdot}64$ sq. inch.

Temperature, Fahr.	No. of experiments.	Strain applied in lbs.	Elongation in inches.	Breaking weight per square inch in lbs.	Remarks.
340°	1	25,260			
	2	26,940			
	3	28,620			
	4	29,460			
	5	30,300			
	6	31,140			
	7	31,980	·1	49,968	=22·307 tons.

In this experiment the plate gave way at the shackle, the bolt which held the plate tearing through the eye, and forcing away a four-sided piece as the plate was about to yield to the weight on the lever. We may therefore safely assume 31,980 or 32,000 lbs. as the ultimate strength or breaking weight of the plate.

TABLE XIII.—Strain applied across the fibre.
Boiler plate; sectional area $=2{\cdot}0 \times {\cdot}34 = {\cdot}68$ sq. inch.

Temperature, Fahr.	No. of experiments.	Strain applied in lbs.	Elongation in inches.	Breaking weight per square inch in lbs.	Remarks.
340°	1	18,540			Broken in hot oil.
	2	20,220			
	3	21,900			
	4	23,580			
	5	25,260			
	6	26,940			
	7	27,780			
	8	28,620	·15	42,088	=18·789 tons.

The mean result of experiments XII. and XIII. is 46,014 lbs., or about 20½ tons per square inch, evidently showing that the iron is in no degree injured by a temperature ranging from zero up to 340°, and this temperature may probably be increased as high as 500° or 600° without seriously impairing the strength, as may be seen in the following Table at nearly 400°.

TABLE XIV.—Strain applied in the direction of the fibre. Boiler plate; sectional area $=2{\cdot}02 \times {\cdot}33 = {\cdot}6666$ sq. inch.

Temperature, Fahr.	No. of experiments	Strain applied in lbs.	Elongation in inches.	Breaking weight per square inch in lbs.	Remarks.
395°	1	18,540			Broken in hot oil.
	2	20,220			
	3	21,900			
	4	23,580			
	5	24,420			
	6	25,260			
	7	26,100			
	8	26,940			
	9	27,780			
	10	28,620			
	11	29,460			
	12	30,300			
	13	30,720	·18	46,086	=20·574 tons.

The only difference between this and the last two experiments is the increased elongation, which in the latter was 1·25, and in the former ·18 inches. However, the elongation of these short specimens cannot always be depended on, as there is considerable difficulty in ascertaining them accurately.

TABLE XV.—Strain applied across the fibre. Boiler plate, sectional area $= 2{\cdot}0 \times {\cdot}31 = {\cdot}62$ sq. inch.

Temperature, Fahr.	No. of experiments.	Strain applied in lbs.	Elongation in inches.	Breaking weight per square inch in lbs.	Remarks.
	1	8,190			
A scarcely perceptible red heat.	2	10,140			
	3	11,820			
	4	13,500			
	5	15,180			
	6	16,860			
	7	18,540			
	8	20,220			
	9	21,900			
	10	23,520	·15	38,032	=16·978 tons.

The plate in this experiment was heated until it became perceptibly luminous in the shade; it was then loaded, as before, until fracture ensued. In this experiment it will be observed that a considerable diminution of strength took place in consequence of the increased temperature, clearly showing that above a certain point the tensile strength of wrought iron is seriously injured. This fact is more strikingly apparent in the next experiment, in which the temperature was raised to a dull red heat, just perceptible in daylight.

Table XVI.

In this experiment a plate of the same description as the last was raised to a dull red heat, when the weight of the lever was allowed to strain the specimen with a force of 18,540 lbs., and fracture immediately ensued. The elongation was ·23.

Sectional area of boiler plate $= 1·96 \times ·31 = ·6076$ sq. inch.

Strain applied across the fibre.

Breaking weight per square inch $= 30,513$ lbs. $= 13·621$ tons.

This experiment is quite conclusive as to the effects produced on wrought iron whenever it approaches a red heat. At that temperature nearly one half its strength is lost; it becomes exceedingly ductile, and is drawn considerably in the direction of the strain before its cohesive powers are destroyed.

The greatly increased ductility of wrought-iron plates, at a dull red heat, is strikingly exemplified in the flues of boilers, whenever the water gets low, or recedes below the surface of the plates, and that more particularly if the plates are immediately over the fire; in such a position the flues readily collapse with a comparatively low pres-

sure. In the bending of a plate, when red hot, a very small force is required; but within limits of temperature not exceeding 400°, it requires nearly the same force to produce collapse as it would at any temperature above 32°, or the freezing point of water.*

Collecting the results of these experiments, tabulated above, it will be necessary to exhibit them in a more condensed form, so as to facilitate comparison, and to deduce the laws which regulate the tensile strength of wrought iron. We may then apply the results of these experiments to a much greater variety of plates produced in the different districts of England. It will be borne in mind

General Summary of Results.

No. of experiment.	Temperature, Fahr.	Breaking weight in lbs.	Breaking weight per square inch in lbs.	Breaking weight per square inch in tons.	Mean breaking weight per square inch in lbs.	Direction of strain in regard to fibre.
I.	0°	33,660	49,009	21·879	49,009	With.
II.	60	31,980	40,357	18·001		Across.
III.	60	27,780	43,406	19·377	44,498	Across.†
IV.	60	31,980	50,219	22·414		With.‡
V.	110	29,460	44,160	19·714		Across §
VI.	112	28,620	42,088	18·789	42,291	With.
VII.	120	37,020	40,625	18·136		With.
VIII.	212°	31,980	39,935	17·828		With.§
IX.	212	30,300	45,680	20·392	45,005	Across.
X.	212	33,660	49,500	22·098		With.
XI.	270	28,620	44,020	19·651	44,020	With.
XII.	340	31,980	49,968	22·307	46,018	With.‖
XIII.	340	28,620	42,088	18·789		Across.
XIV.	395	30,720	46,086	20·574	46,086	With.
XV.	Scarcely red	23,520	38,032	16·978	34,272	Across.
XVI.	Dull red	18,540	30,513	13,621		Across.¶

* We hope in a short time to give a series of experiments on the resistance of wrought-iron plates and bars to a transverse and compressive force at various temperatures.

† Some steely spots in fracture.

‡ Fissure containing scoria.

§ Too high, fracture very uneven.

‖ Too low, tore through the eye.

¶ Too high, see Table.

that the ordinary Staffordshire plates, such as those experimented upon (unless they are double-worked), are rather inferior in quality to the Shropshire and Derbyshire plates, and much more so to those manufactured at the Lowmoor and Bowling works. Hence the comparison will only hold good between the Staffordshire plates in each case.

From the above Table we may deduce the following:—

Temperature, Fahr.	Drawn asunder in the direction of the fibre.		Drawn asunder across the fibre.	
	Breaking weight per square inch in lbs.	Breaking weight per square inch in tons.	Breaking weight per square inch in lbs.	Breaking weight per square inch in tons.
0°	49.009	21·879		
60	50,219	22·414†	41,881	18·689*
114	41,356	18·462	44,160	19·714‡
212	44,717	19·963§	45,680	20·392
270	44,020	19·651		
340	49,968	22·307‖	42,088	18·789
395	46,086	20·574		
Red			34,272	15·299¶

From the experimental inquiry into the strength of wrought-iron plates, as applied to ship-building, we have the following results:—**

* Some steely spots in fracture.
† Fissure containing scoria.
‡ Too high, fracture very uneven.
§ Did not break at the smallest section.
‖ Too low, tore through the eye.
¶ Too high, see Table.
** Useful Information, First Series, Appendix I.

	Mean breaking Weight, in the direction of the Fibre, in tons per square inch.	Mean breaking Weight, across the Fibre, in tons per square inch.
Yorkshire plates . . .	25·770	27·490
Yorkshire plates . . .	22·760	26·037
Derbyshire plates . .	21·680	18·650
Shropshire plates . .	22·826	22·000
Staffordshire plates . .	19·563	21·010
Mean . . .	22·519	23·037

Now if we compare the ultimate strength of the Staffordshire plates in the above Table with those since experimented upon, we shall have, taking those in which the strain was applied in the direction of the fibre, for the former 19·563 tons per square inch, and for a mean of nine experiments of the latter, ranging in temperature from zero to 395°, 20·408 tons per square inch. Taking those torn asunder across the fibre, we have for Staffordshire plates in the above Table 21·010, and for those since experimented on 19·254 tons* per square inch, which on comparison give the following ratios of results: —

Staffordshire plates, torn in the direction of the fibre, at a mean temperature of 191°=20·408 tons, and those (in the above Table) at the temperature of the atmosphere, or about 60°=19·563 tons, or in the ratio of 1·: ·96 nearly, a close approximation in tensile strength in the two series of experiments.

Those torn across the fibre, at a mean temperature of 156°, gave a tensile strength=19·254 tons; those at the temperature of atmosphere 60°, as shown in the previous experiments=21·010 tons, or in the ratio of 1 : 1·091.

* The mean temperature of nine specimens, broken in the direction of the fibre, is 191°; and the mean temperature of five, broken across the fibre, excluding red heat, is 156°.

The above results indicate great uniformity in the ultimate strength of Staffordshire plates, which may safely be taken at 20 tons per square inch at all temperatures, between the extremes of zero and 400° Fahr., that is, under a dead weight calculated to destroy the cohesive powers of the material. To what extent these plates would resist impact, at various degrees of temperature, we have yet to determine; but assuming that iron is more liable to fracture from an impactive force at a very low temperature, it will be safer to calculate on a reduction of their resisting powers, at the lower temperatures under 32° Fahr., or the freezing-point of water.

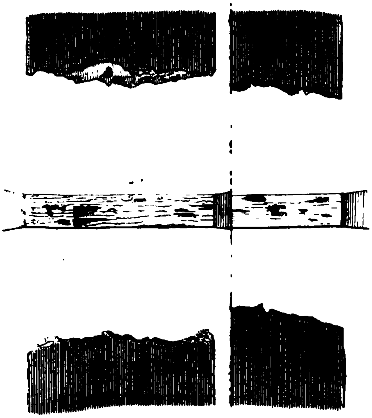
These experiments might be multiplied to a great extent, in order to determine the strength of plates under the varied conditions of temperature in regard to compression, extension, and the force of impact; but we have already shown in former experiments, and those now recorded above, that iron is not seriously affected by those changes, and we trust the foregoing results will prove sufficient to enable the practical engineer to calculate the resisting powers of iron plates, under all the changes of temperature, from zero up to a red heat.

In Plate IV. will be found drawings of most of the fractured surfaces of the boiler plate, numbered to correspond with the preceding tables.

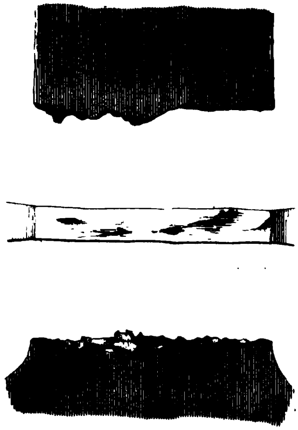
Experiments on the Tensile Strength of Rivet Iron.

At the time when the preceding experiments were instituted, it was considered expedient to make them on plates of ordinary quality, and of the description in general use. For this purpose Staffordshire plates were selected, as being of medium quality, such as are employed in the construction of boilers, ship-building, &c. Plates of a higher character, such as the Lowmoor and *double-worked*

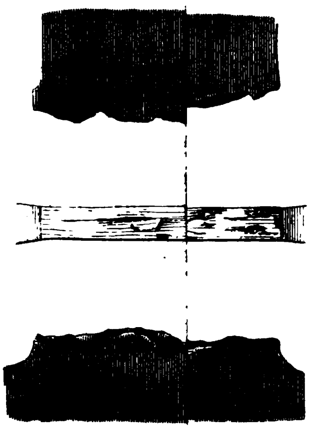
Plate IV



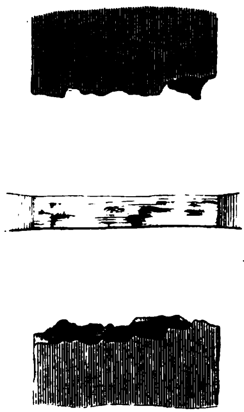
Experiment 1 6



7



Experiment



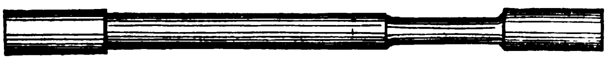
16

qualities, might have been selected; but those most in demand, and which are manufactured in large quantities, were considered more desirable, although it left untouched a question of some importance in regard to the influence of heat upon the finer qualities, generally known as "*scrap*" and "*fagotted*" iron. This description of iron is forged from old iron scrap, and rolled into bars for bolts and rivets. It is a fine ductile iron of great tenacity, and works freely under the hammer; and it was determined to apply to it the same experimental tests as had been applied to the Staffordshire plates.

From the results of these experiments, it will be seen that they indicate precisely the same law as was found to influence the Staffordshire plates, the maximum strength being at a temperature of 325°, rather higher than that indicated by the plates. This is irrespective of the superior strength of the bar iron as compared with that of the plates.

Having prepared the lever, as before, a long bar, $\frac{7}{8}$ths of an inch in diameter, was selected and cut into lengths, which were then reduced to the form shown in the

Fig. 26.



annexed sketch, with shoulders to receive the shackle. The specimens, when immersed in the bath, were drawn asunder by the same process as that described for the plates.

Experiments to ascertain the Influence of Temperature on the Tensile Strength of Rivet Iron.

TABLE XVII.—Area of section=·2485 sq. ins.

Temperature, Fahr.	No. of Experiments.	Strain applied in lbs.	Elongation in inches.	Breaking Weight per square inch in lbs.	Remarks.
−30°	1	9,205			Broken in a mixture of pounded ice and crystallised chloride of calcium.
	2	9,415			
	3	11,648			
	4	10,045			Figures of some of the fractured specimens will be found in Pl. III. fig. 1, numbered to correspond with the tables.
		* * * *			
	58	15,610			
	59	15,715	·80	63,239	=28·231 tons.

From the above it will be observed that the strength of the best quality of bar iron greatly exceeds that of the plates, being in this experiment two-fifths more, and in some experiments, at higher temperatures, nearly double that of the Staffordshire plates.

TABLE XVIII.—Sectional area=·2485 sq. ins.

Temperature, Fahr.	No. of Experiments.	Strain applied in lbs.	Elongation in inches.	Breaking Weight per square inch in lbs.	Remarks.
+ 60°	1	12,565			
	2	13,405			
	3	13,812			A large bright spot, like steel, in fracture.
	4	14,035			
		* * * *			
	16	15,295			
	17	15,400	·82	61,971	=27·665 tons.

There is a slight diminution in the strength of this bar as compared with the previous experiment at—30°, but

the discrepancy is scarcely appreciable, and may easily be accounted for by inequalities in the forging or rolling of the bar.

TABLE XIX.—Sectional area = ·2485 sq. ins.

Temperature, Fahr.	No. of Experiments.	Strain applied in lbs.	Elongation in inches.	Breaking Weight per square inch in lbs.	Remarks.
60°	1	9,415			
	2	10,255			
	3	12,565			Drew out at shoulder.
	4	12,985			
		* * * *			
	30	15,715			
	31	15,820	·56	63,661	= 28·419 tons.

The strength of the bar in this experiment is a trifle in excess of those fractured at $-30°$ and 60°. It would have been rather stronger had it been rounded at the shoulder like the others to prevent its pulling out there, as shown in the figure. However, there is little difference in the strength of the material through a range of 90° of temperature.

TABLE XX.—Sectional area = ·2485 sq. ins.

Temperature, Fahr.	No. of Experiments.	Strain applied in lbs.	Elongation in inches.	Breaking Weight per square inch in lbs.	Remarks.
114°	1	10,885			Pulled out at shoulder. After between 13,000 and 14,000 lbs. had been laid on, only 105 lbs. were added at a time, as it gave more correct indications of the strength as the bars approached fracture.
	2	12,565			
	3	13,405			
	4	13,615			
		* * * *			
	41	17,500			
	42	17,605	·56	70,845	= 31·627 tons.

It has already been observed that the whole of the specimens for experiment were cut from one bar, and as each experiment was conducted with great care, both in preparing the specimens and laying on the weights, we are bound by the results to believe that the increased strength of this description of iron is due entirely to the increase of temperature. In this experiment it will be seen that the resisting power of the bar ruptured at 114° was to that of the bar ruptured at 60° (Table XIX.) as 1 : ·898.

TABLE XXI.—Sectional area = ·2485 sq. ins.

Temperature, Fahr.	No. of Experiments.	Strain applied in lbs.	Elongation in inches.	Breaking Weight per square inch in lbs.	Remarks.
212°	1	12,565			
	2	12,985			
	3	13,405			
	4	13,825			
	5	14,245			
		* * * *			
	76	21,805			At this point it was discovered that the bar was cutting into the shackle; the experiment was therefore discontinued till a new shackle could be prepared, and it was then repeated.
	1	12,565			
	2	12,985			
	3	13,405			
	4	13,825			
		* * * *			
	56	19,285	·64		
Mean . .		20,545		82,676	= 36·900 tons.

This bar tore into the shackle, so that the strain was not thrown properly on it; the experiment was therefore discontinued, and another shackle substituted with the bearing-edges steeled. When the same bar was tried again, having been injured in the previous experiment, it

broke with 19,285 lbs. Under these circumstances, we have taken the mean of the two experiments, $\frac{21,805+19,285}{2}=20,545$ as the breaking weight, as recorded in the Table.

TABLE XXII.—Sectional area = ·19635 sq. ins.

Temperature, Fahr.	No. of Experiments.	Strain applied in lbs.	Elongation in inches.	Breaking Weight per square inch in lbs.	Remarks.
212°	1	12,565			
	2	13,405			Bar defective: a large longitudinal fissure, filled with scoria.
	3	14,245			
	4	14,350			
	5	14,455			
	6	14,560	·47	74,153	= 33·104 tons.

There is a progressive increase in the strength of the bars as the temperature ascends, Table XX. exhibiting an increase of 11,831 lbs., and Table XXII. an increase of 3308 lbs. over the breaking weight at 114°. Taking the mean of the two last experiments, we have an increase of 7569 lbs. over the breaking weight in Experiment XX.

TABLE XXIII.—Sectional area = ·2485 sq. ins.

Temperature, Fahr.	No. of Experiments.	Strain applied in lbs.	Elongation in inches.	Breaking Weight per square inch in lbs.	Remarks.
212°	1	14,245			
	2	15,925			
	3	16,135			
	4	16.345			
		* * * *			
	39	20,020			
	40	20,125	·66	80,985	= 36·154 tons.

This experiment being at the same temperature as the two last, viz. 212°, it will be proper to take the mean of

the last three Tables as the breaking weight at that temperature, $\frac{82,676+74,153+80,985}{3}=79,271$ lbs. per square inch = ultimate breaking weight at 212°.

TABLE XXIV.—Sectional area = ·19635 sq. ins.

Temperature, Fahr.	No. of Experiments.	Strain applied in lbs.	Elongation in inches.	Breaking Weight per square inch in lbs.	Remarks.
250°	1	10,045			
	2	10,885			
	3	11,725			
		* * * *			
	43	15,925			
	44	16,135	·6	82,174	= 36·684 tons.

Here again, in the above experiment, is a perceptible increase of strength, as the temperature rises 38°, from 79,271 to 82,174 lbs. per square inch, and so in the next Table, where the increase is still greater.

TABLE XXV.—Sectional area = ·2485 sq. ins.

Temperature, Fahr.	No. of Experiments.	Strain applied in lbs.	Elongation in inches.	Breaking Weight per square inch in lbs.	Remarks.
270°	1	12,565			
	2	13,405			
	3	14,245			
	4	15,085			
	5	15,400			
	6	15,925			
	7	16,345			
		* * * *			
	47	20,545			
	48	20,650	·74	86,056	= 38·417 tons.

The increase of 20° of temperature in this experiment, gives a corresponding increase of strength of 3882 lbs.

per square inch, something more than the increase exhibited in the previous experiment. There is, however, a remarkable coincidence in the ratio of the strengths as they rise with the increase of temperature, the only exceptions being those of Tables XVII. and XXII., but in both cases the anomaly is sufficiently explained by the state of the fracture.

TABLE XXVI.—Sectional area=·19635 sq. ins.

Temperature, Fahr.	No. of Experiments.	Strain applied in lbs.	Elongation in inches.	Breaking Weight per square inch in lbs.	Remarks.
310°	1	12,565			
	2	14,245			
	3	15,085			
	4	15,295			
	5	15,715			
	6	15,820	·63	80,570	=35·968 tons.

In this experiment it will be observed that there is a falling off in tenacity with the increase of temperature from 86,056 to 80,570 lbs. per square inch. It is difficult to account for this discrepancy, as the fracture in this, as in the previous and succeeding experiments, appeared sound and free from flaws of any description.

TABLE XXVII.—Sectional area=·19635 sq. ins.

Temperature, Fahr.	No. of Experiments.	Strain applied in lbs.	Elongation in inches.	Breaking Weight per square inch in lbs.	Remarks.
325°	1	10,045			
	2	10,885			
	3	11,725			
		****			
	53	17,080			
	54	17,185	·6	87,522	=39·072 tons.

The above bar, although of the same quality and appearance as that in the previous experiment, gives no less than 6952 lbs., upwards of three tons, greater tenacity than its predecessor. The former appeared equally tough and fibrous in the fracture, and the elongation in the same distance was rather more than in the latter, and yet it is about one-twelfth weaker.

TABLE XXVIII.—Sectional area = ·2485 sq. ins.

Temperature, Fahr.	No. of Experiments.	Strain applied in lbs.	Elongation in inches.	Breaking Weight per square inch in lbs.	Remarks.
415°	1	12,565			
	2	14,245			
	3	15,085			
	4	15,925			
	5	16,765			
		* * * *			
	38	20,230			
	39	20,335	·64	81,830	= 36,531 tons.

In this experiment there is a decrease in the strength with an increase of temperature of 90°, but in the next experiment, with a further increase of 20°, the strength again rises from 81,830 to 86,056, or nearly two tons, which shows that the increase of 100° of temperature has not seriously affected the molecular constitution of the iron. This irregularity, after so constant an increase of strength, indicates that we have about reached the maximum strength of the material. We shall see hereafter that the increase of strength from — 30° to 325° has been four-tenths, nearly one-half.

TABLE XXIX.—Sectional area = ·2485 sq. ins.

Temperature, Fahr.	No. of Experiments.	Strain applied in lbs.	Elongation in inches.	Breaking Weight per square inch in lbs.	Remarks.
435°	1	12,565			
	2	13,405			
	3	13,812			
	4	14,035			
	5	14,245			
	6	14,665			
	7	15,085			
		****			
	65	21,280			
	66	21,385	·74	86,056	= 38·415 tons.

The difference between this and the last experiment is about one-eighteenth part of the former in favour of the latter. This difference we cannot account for by an examination of the fractures; but taking the mean of the two, and comparing it with Table XXVII., it appears that we have passed the maximum strength, and recede from it in the ratio of 87,522 : 83,943, or as 1 : ·959.

TABLE XXX.—Sectional area = ·2485 sq. ins.

Temperature raised to red heat, visible by daylight.
Broke with the weight of the lever = 8965 lbs.
Elongation = ·55.
Breaking weight per square inch = 36,076 lbs. = 16·105 tons.

In this experiment, as in those on the plates, the tenacity of the iron is seriously injured before the temperature reaches dull red heat; and when that point is attained, it has lost more than one-half its powers of resistance to strain. At this high temperature it becomes exceedingly ductile and weak when subjected to any

description of force, inasmuch as it becomes so pliable that it is immaterial whether the strain applied is compressive, tensile, or torsional. Under any of these forces it is not to be depended upon at a temperature bordering upon redness.

Collecting the results of the foregoing experiments in their consecutive order into a Table, we see that the maximum strength of bars appears to be attained at a below mean temperature of about 320°. This is ~~above~~ the temperature at which the maximum strength of the plates was attained; but it is to be remembered, that little change is observable in the strength of the plates, whilst that of the bars is increased nearly one-half.

This fact is worthy of notice, inasmuch as in countries where the climate is hot and never descends below freezing, the best bar iron will retain a power of resistance equal to 29 tons upon the square inch, whereas in colder and more northerly districts it would not be safe to calculate upon more than 28 tons to the square inch.

General Summary of Results.

Temperature, Fahr.	No. of Experiment.	Breaking Weight in lbs.	Elongation in inches.	Breaking Weight per square inch in lbs.	Breaking Weight per square inch in tons.	Mean breaking Weight per square inch in lbs.	Remarks.
−30°	XVII.	15,715	·80	63,239	28·231	63,239	Too low.
+60	XVIII.	15,400	·82	61,971	27·665	62,816	Too low.
60	XIX.	15,820	·56	63,661	28·419		
114	XX.	17,605	·56	70,845	31·627	70,845	Too low.
212	XXI.	20,545	·64	87,676	36 900		
212	XXII.	14,560	·47	74,153	33·104	79,271	
212	XXIII.	20,125	·66	80,985	36·154		
250	XXIV.	16,135	·60	82,174	36·684	82,636	
270	XXV.	20,650	·74	83,098	38·417		
310	XXVI.	15,820	·63	80,570	35·968	84,046	
325	XXVII.	17,185	·60	87,522	39 072		
415	XXVIII.	20,335	·64	81,830	36·531	83,943	
435	XXIX.	21,385	·74	86,056	38·415		
Red heat.	XXX.	8,965	·55	36,076	16·105	35,000	Too high.

In the above Table we perceive a steady improvement in the strength of the iron from 60° up to 325°, where the

maximum appears to be attained. As already noticed, this improvement does not present itself in the inferior descriptions of irons, such as the plates tested in the preceding experiments. This may arise from the different processes pursued in the manufacture, the bars being rendered fibrous and ductile, in the first instance, under the hammer, and this is further improved by reheating them and passing them between the rolls. Bar iron will thus be drawn by the hammer and rolls to from twenty to twenty-five times its original length; whilst plates, such as we have selected, never come under the hammer, and seldom exceed six or eight times the length of the original shingle after passing through the rolls.

On comparing these results with those of a similar quality of iron, viz. S.C. ♛ bar iron, experimented upon at Woolwich Dockyard, it will be found that a corresponding and progressive increase of strength is equally apparent as in the above experiments; that increase, however, arising from a different cause, namely, the repeated fracture of the bars as exhibited in the following Table:—

Mark.	First Breakage.		Second Breakage.		Third Breakage.		Fourth Breakage.		Reduced from 1·37
	Tons.	Stretch in 54 inches.	Tons.	Stretch in 36 inches.	Tons.	Stretch in 24 inches.	Tons.	Stretch in 15 inches.	
		in.		in.		in.		in.	
A	33·75	9·125	35·5	2·00					
C	33·75	9·250	35·25	·25	37·00	1·00	38·75		1·25
E	32·5	9 250	34·75	1·25					
F	33·25	10·500	35·50	1·12	37·25	·62	40·40	. .	1·18
G	32·75	8·500	35·00	1·25	37·5	. .	40 41	. .	1·25
H	33·75	10·625	36·25	1·87					
I	33·50	8·375	34 50	·62	36 5	1 50			
J	33·50	9·250	36 00	25	36·75	1·120	41·75	. .	1·25
L	32·25	Defective	36·50	1·5	37·75	. .	41·00	·31	1·25
M	30·25	Defective	36·50	·62	37·75	0·6	38·50	·06	1·25
Mean . . .	32·92	. . .	35·57	. .	37·21	. .	40·16	. .	1·24
Mean per square inch	~~23·94~~	. . .	25·86	. .	27·06	. .	29·20	. .	·90

24.04 25.93

From the above it will be seen that the mean strength of the bars was 24 tons, whilst that of the rivet iron was 28 tons per square inch, at a temperature of 60°, and that the former attained its maximum strength of 29 tons from repeated breakages, whilst the latter reached a strength of 37 tons by an increase of temperature up to 317°. These are curious and interesting facts, exhibiting a parallel increase of strength, in the one case resulting from repeated strains, in the other from increase of temperature.

The foregoing Table indicates a progressive increase of strength, notwithstanding the reduced sectional area of the bars. This fact is of considerable importance, as it shows that a severe tensile strain is not injurious to the bearing powers of wrought iron, even when repeated to the extent of four times. In practice, it may not be prudent to test bars and chains to their utmost limit of resistance; it is however satisfactory to know, that in cases of emergency those limits may be approached without incurring a serious risk of injury to the ultimate strength of the material.

It is further important to observe, that the elongations are not in proportion to the forces of extension; thus in the bar A, the elongation of a bar, 54 inches long with 33·25 tons, is 10·5 inches, giving an elongation per unit of weight and length $= \dfrac{10 \cdot 5}{33 \cdot 25 \times 54} = \cdot 0058$, whereas an additional weight of 2·25 tons produces an elongation of 1·25 inches in 36 inches of length of bar, giving an elongation per unit of length and weight$= \dfrac{1 \cdot 25}{2 \cdot 25 \times 36} = \cdot 0154$; that is, the elongation in this case is about three times that in the former.

From the experiments on rivet iron we have a mean elongation, in fourteen experiments, of ·643 inches in 2½

inches, or $\frac{\cdot 643}{2\cdot 5} = \cdot 257$ per unit of length; and in those on the S.C. ♕ bars, we have a mean elongation of ·274, as given in the following Table:—

Length of Bar.	Elongation.	Elongation per Unit of Length.
in.		
120	26·0	·216
42	9·8	·233
36	8·8	·244
24	6·2	·258
10	4·2	·420

Hence it appears that the rate of elongation of bars of wrought iron increases with the decrease of their length; thus while a bar of 120 inches has an elongation of ·216 inch per unit of its length, a bar of 10 inches has an elongation of ·42 per unit of its length, or nearly double what it is in the former case. The relation between the length of the bar and its maximum elongation per unit, may be approximately expressed by the following formula, viz.—

$$l = \cdot 18 + \frac{2\cdot 5}{L},$$

where L represents the length of the bar, and l the elongation per unit of length of the bar.

It is difficult to measure accurately the elongations in $2\frac{1}{2}$ inches, but the following Table shows the elongation per unit of weight and length at various temperatures, as exhibited in the experiments on rivet iron.

Temperature, Fahr.	Elongation per ton per inch.	Mean Elongation per Unit of Length and Weight.
-30°	·00284	·00284
+60	·00297	·00247
60	·00197	
114	·00177	·00177
212	·00173	·00162
212	·00142	
212	·00182	
250	·00164	·00178
270	·00192	
310	·00175	·00164
325	·00153	
415	·00175	·00183
435	·00192	
Red heat.	·00341	·00341

These results show that the elongation per unit of length and weight somewhat decreases upwards towards the temperature of maximum strength, and thence decreases, so that whilst the elongation is nearly the same at all ordinary temperatures, it is more than doubled at red heat.

IV.

ON THE COMPARATIVE VALUE OF VARIOUS KINDS OF STONE, AS EXHIBITED BY THEIR POWERS OF RESISTING COMPRESSION.

(From the Memoirs of the Manchester Philosophical Society.)

Our knowledge of the properties of stone, viewed as a building material, is very imperfect, and our architects and stonemasons have yet much to learn concerning the difference between one kind of stone and another, both as regards their chemical constitution, their durability, and their powers of resisting compression. On this subject we have the experiments of Gauthey, Rondelet, and Rennie, which to some extent supply the deficiency and furnish data for the resistance to a crushing force of a considerable variety of stone. These are, however, to some extent inapplicable to the purposes for which such data are required; and not finding them in exact accordance with the results of some experiments recently made, I have endeavoured to inquire into the causes of the discrepancy, and to account for the difference.

Stone is found in various forms and conditions, embedded in and stratified under the earth's surface. That portion of it which is used for building purposes, is a dense coherent brittle substance, sometimes of a granulated, at others, of a laminated structure. These qualities varying according to its chemical constitution and the mode in which it has been deposited. Sometimes the laminated

and granular rocks alternate with each other; at others, a rock of a mixed form prevails, partaking of the characteristics of both structures. Independent of these properties is its power of resistance to compression, which depends chiefly upon its chemical combinations and the pressure to which it has been subjected whilst under the earth's surface from the weight of superincumbent materials. The granite also, and other igneous rocks, owe their hardness to their having crystallised more or less rapidly from a fused mass.

In attempting to ascertain the ultimate powers of resistance of rocks which have been deposited by the action of water, it is necessary to observe the direction in which the pressure is applied, whether in the line of cleavage, or at right angles to it. In nearly all of the following experiments this precaution was attended to, and it will be seen that the strength is far greater when the force is exerted perpendicularly to the laminated surface, than when it is applied in the direction of the cleavage. In building with such stone, it is also important that it should be laid in the same position as that in which it is found in the quarry, as the action of rain and frost rapidly splits off the laminæ of the stone when it is placed otherwise. The strength of the igneous, or crystalline rocks, is the same in every direction, owing to the arrangement of the particles of which they are composed.

It might have been advantageous to have ascertained, by analysis, the chemical composition of the substances experimented on; but as this varies in almost every locality, and that in accordance with the superincumbent and surrounding strata, this is of less consequence in practice than a knowledge of absolute facts in connection with the properties of the material. Deductions from direct experiment are of no small importance to the architect and builder, as he should not only be acquainted with the

strengths and other properties of the material on which he works, but also with the changes of those qualities under the varied forms of stratified, metamorphic, and igneous rocks.

On the durability of the specimens, I have made no further inquiry than in regard to their power of resistance to strain. Any addition would require a separate investigation into the chemical constituents of the different specimens, and into those changes to which stone of almost every description is subjected when exposed to the action of the atmosphere. In omitting this branch of the investigation I have not forgotten its importance, but have very properly left its development to abler hands.

Before giving the results of the inquiry, I may observe that a portion of the experiments were undertaken at the request of Mr. E. W. Shaw, the surveyor of the borough of Bradford, in Yorkshire, in order to ascertain the best and strongest qualities of stone for paving the streets of that town. The following Tables give the result of the experiments on fifteen specimens of Yorkshire sandstone, and on some specimens from Wales and other places, as follow: —

Experiments to determine the force necessary to fracture, and subsequently to crush, 2-in. cubes of Sandstone from the Shipley quarries, Bradford. The pressure applied in the direction of the cleavage.

No. of Experiment.	Weights laid on in lbs.	Remarks.	No. of Experiment.	Weights laid on in lbs.	Remarks.
Specimen No. 1. Shipley.			Specimen No. 2. Heaton.		
12	31,732		11	31,732	
13	33,524	fractured.	12	33,524	fractured.
..	...	...	..	...	...
16	38,900	crushed.	16	40,692	crushed.

No. of Experiment.	Weights laid on in lbs.	Remarks.	No. of Experiment.	Weights laid on in lbs.	Remarks.
Specimen No. 3. Heaton Park.			Speeimen No. 4.		
8	26,356		This specimen was defective and crushed as the first weight, 28,148 lbs., was laid on.		
9	28,148				
10	29,940	fractured.			
11	31,732	crushed.			
Specimen No. 9. Old Whatley.			Specimen No. 10. Manningham Lane.		
11	31,732		8	26,356	
12	33,524		9	28,148	fractured.
13	35,316	fractured and crushed suddenly.	. .	. . .	. . .
			14	37,108	crushed.

The results of the Experiments 1, 2, 3, 9, 10, fractured and crushed in the line of cleavage, are given in the following Table.

No. of Specimen.	Locality.	Size.	Weight at which it fractured.	Weight at which it crushed.
1	Shipley, Bradford .	2-in cube.	33,524	38,900
2	Heaton . . .	"	33,524	40,692
3	Heaton Park . .	"	29,940	31,732
9	Old Whatley . .	"	35,316	35,316
10	Manningham Lane	"	28,148	37,108
	Mean		32,090	36,749

Experiments to determine the force required to fracture, and subsequently to crush, 2-in. cubes of Sandstone from the Shipley and other quarries, near Bradford. Pressure being applied at right angles to the cleavage.

No. of Experiment.	Weights laid on in lbs.	Remarks.	No. of Experiment.	Weights laid on in lbs.	Remarks.
Specimen No. 5. Idle Quarry.			Specimen No. 6. Jegrum's Lane.		
15	38,900		18	44,276	
16	40,692		19	45,172	fractured.
17	42,484	fractured.	. .	. . .	. . .
18	43,380	crushed.	22	47,860	crushed.
Specimen No. 7. Spinkwell.			Specimen No. 8. Coppy Quarry.		
10	29,940		14	37,108	first fracture.
11	31,732	fractured.	. .	. . .	. . . . .
. .	. . .	. . .	16	39,796	second fracture.
14	37,108	crushed.	. .	. . .	. . . . .
			18	41,588	crushed.
Specimen No. 11 failed.					

Results of Experiments on Specimens 5, 6, 7, 8, fractured and crushed at right angles to the cleavage.

No. of Specimen.	Locality.	Size.	Weight at which it fractured.	Weight with which it crushed.
5	Idle Quarry, Bradford . .	2-in. cube	42,484	43,380
6	Jegrum's Lane .	"	45,172	47,860
7	Spinkwell . .	"	31,732	37,108
8	Coppy Quarry .	"	37,108	41,588
	Mean .	. .	39,124	42,484

By the foregoing experiments it will be observed that the resisting powers of stone to compression, are greatest when the pressure is applied perpendicularly upon the bed or laminated surface, and that in the ratio of 100: 82 in the force required to fracture, and 100: 86 in the force required to crush this description of stone. Hence, as already observed, the powers of resistance of every description of laminated stone, are most effective when the beds are placed horizontally or perpendicularly to the direction of the pressure, and this position is the more important when the stone is exposed to the atmosphere, as it partially prevents the absorption of moisture, which in winter tends to destroy the material by the contraction of the stone and the expansion of the water at low temperatures.

Experiments to determine the force required to fracture and crush 1-in., $1\frac{1}{2}$-in., and 2-in. cubes of stones from Scotland, Wales, and other places.

No. of Experiment.	Weight laid on in lbs.	Remarks.	No. of Experiment.	Weight laid on in lbs.	Remarks.
Specimen No. 12. Grauwacke. Penmaenmawr, Wales. 2-in. cube.			Specimen No. 14. Granite. Mount Sorrel. 2-in. cube.		
16	40,692	slight fracture.	19	46,068	
..	.....	......	20	47,860	
29	63,988	second fracture.	21	49,652	
30	65,780		22	51,444	fractured, and after a slight rest crushed.
31	67,572	crushed.			
Specimen No. 15. Grauwacke. Ingleton. 2-in. cube.			Specimen No. 16. Granite. Aberdeen. 2-in cube.		
13	35,316	first fracture.	8	26,356	
..	.....	......	9	27,546	fractured.
20	47,860	second fracture.	10	28,148	
..	.....	......	11	28,340	not crushed.
25	53,236	not crushed.			

No. of Experiment.	Weight laid on in lbs.	Remarks.	No. of Experiment.	Weight laid on in lbs.	Remarks.
Specimen No. 17. Syenite. Mount Sorrel. 2-in. cube.			Specimen No. 18. Granite. Bonaw. 1½-in. cube.		
17	42,484		2	15,604	
18	44,276		3	17,396	fractured in two
19	46,068		. .	. . . . . .	nearly equal pts.
20	47,284	crushed.	7	24,564	crushed.
Specimen No. 19. Furnace Granite. Inverary. 1½-in. cube.			Specimen No. 20. Granite. A. 1½-in. cube.		
4	19,188		4	19,188	
5	20,980		5	20,980	
6	22,772		6	22,772	fractured.
7	24,564	crushed.	7	24,564	crushed.
Specimen No. 21. Limestone. B. 1½-in. cube.			Specimen No. 22. Limestone. C. 1½-in. cube.		
1	13,812		2	15,604	
2	15,604		3	17,396	
3	17,396	fractured.	4	18,292	fractured.
4	19,188	crushed.	5	19,188	crushed.
Specimen No. 23. Magnesian Limest. Anston. 1-in. cube.			Specimen No. 24. Magnesian Limest. Worksop. 1-in. cube.		
1	1258		13	3,834	
2	2154	fractured.	14	3,946	fractured.
. .	. . . .	. . . . . .	. .	. . . .	. . . . . .
10	3050	crushed.	38	7,098	crushed.
Specimen No. 25. Sandstone. 1-in. cube.			Specimen No. 26. Sandstone. 2-in. cube.		
8	2938		11	9,770	
9	3050	fractured.	12	10,218	fractured.
. .	. . . .	. . . . . .	. .	. . . . . .	. . . . . .
13	3498	crushed.	20	12,228	crushed.

Results of Experiments on stone from North Wales and other places. Specimens Nos. 12, 14, 17, 18, 19, 20, 21, 22, 23, 24, 25, *and* 26.

No. of Specimen.	Description of Stone.	Locality.	Size.	Weight with which it fractured, in lbs.	Weight with which it crushed, in lbs.	Pressure required to crush a 2-in. cube, in lbs.
12	Grauwacke.	Penmaenmawr . .	2-in. cube.	40,692	67,572	67,572
14	Granite. .	Mount Sorrel . .	"	51,444	51,444	51,444
17	Syenite . .	" " . .	"	47,284	47,284	47,284
18	Granite. .	Bonaw, Inverary .	1½-in. cube	17,396	24,564	43,669
19	"	Furnace, " . .	"	24,564	24,564	43,669
20	"	(A)	"	22,772	24,564	43,669
21	Limestone .	(B)	"	17,396	19,188	34,112
22	"	(C)	"	18,292	19,188	34,112
23	"	Anston	1-in. cube.	2,154	3,050	12,200
24	"	Worksop . . .	"	3 946	7,098	28,392
25	Sandstone .	. . . . . .	"	3,050	3,498	13,992
26	"	. . . . . .	2in. cube.	10,218	12,228	12,228

The Welsh specimen of grauwacke, from Penmaenmawr, exhibits great powers of resistance, nearly double that of some of the Yorkshire sandstones, and about one-third in excess of the granites, excepting only the granite from Mount Sorrel, which is to the Welsh grauwacke, as ·757 : 1. Some others, such as the Ingleton grauwacke, supported more than the granites, but are deficient when compared with that from Penmaenmawr. The specimen No. 23 is the stone of which the Houses of Parliament are built. Specimens Nos. 25 and 26 were broken to show experimentally the ratio of the powers of resistance as the size is changed. The results are sufficiently near to prove that the crushing weights are as the areas of the surface subjected to pressure.

The specific gravity and porosity of the different kinds of rock vary greatly, and Mr. Shaw, in his desire to obtain the best quality of Yorkshire paving stone, had those from the neighbourhood of Bradford carefully tested

in regard to their powers of absorption; the experiments, which were conducted with great precision, gave the following results.

Experiments to ascertain the amount of Water absorbed by various kinds of Stone.

No. of Specimen.	Description of Stone.	Locality.	Weight before immersion.	Weight after immersion for 48 hours.	Difference of Weight.	Proportion absorbed, one part in
			lbs.	lbs.	lbs.	
1	Sandstone .	Shipley	5·4687	5·5546	·0859	63·6
2	„	Heaton	5·2578	5·3632	·1054	49·8
3	„	Heaton Park . .	5·1718	5·2896	·1171	44·1
4	„	Spinkwell . . .	5·2968	5·4726	·1758	30·1
5	„	Idle Quarry . . .	5·7178	5·8203	·1016	56·3
6	„	Jegrum's Lane . .	5·5976	5·7187	·1211	46·2
7	„	Spinkwell . . .	5·6757	5·7851	·1094	53·8
8	„	Coppy Quarry . .	5·5703	5·6914	·1211	46·0
9	„	Old Whatley . .	5·4726	5·6132	·1406	38·9
10	„	Manningham Lane .	5·4882	5·6093	·1211	46·3
11	„	„ „	5·6289	5·7539	·1250	45·0
12	Grauwacke .	Wales	6·4101	6·4140	·0039	1641·0
13	Granite . .	Mount Sorrel . .	5·6875	5·6992	·0117	485·0
14	„	„ „ . .	5·8007	5·8124	·0117	495·0
15	Grauwacke .	Ingleton . . .	5·7500	5·7539	·0039	1962·6

From the above Table it will be observed that specimen No. 15, the Ingleton grauwacke, is the least absorbent, and No. 12, the Welsh grauwacke, absorbs almost as little, while Nos. 9 and 14 of the sandstones absorb most. The granites, though closely granulated, take up much more water than the grauwackes, but less than the sandstones. The resistance of the grauwacke specimens to the admission of water is four times that of the granite, and thirty-six times that of sandstone, such as is found in the Yorkshire quarries.

No. of Specimen.	Description of Stone.	Locality.	Size.	Specific Gravity.	Pressure to fracture Specimen.	Pressure to crush Specimen.	Pressure per square inch to crush Specimen.	Cubic feet in a ton.	Ratios of Powers of Absorption.
			cube.		lbs.	lbs.	lbs.		1 in
1	Sandstone.	Shipley* . . .	2-in.	2·452	33,524	38,900	9,725	14·616	63·6
2	"	Heaton* . . .	"	2·420	33,524	40,692	10,173	14·809	49·8
3	"	Heaton Park* .	"	2·385	29,940	31,732	7,933	15·027	44·1
4	"	Spinkwell. . .	"	2·329	defec	tive.	. . .	15·388	30·1
5	"	Idle Quarry† . .	"	2·464	42,484	43,380	10,845	14·545	56·3
6	"	Jegrum's Lane† .	"	2·400	45,172	47,860	11,965	14·933	46·2
7	"	Spinkwell† . .	"	2·456	31,732	37,108	9,277	14·592	53·8
8	"	Coppy Quarry* .	"	2·408	37,108	41,588	10,397	14·833	46·0
9	"	Old Whatley* .	"	2·415	35,316	35,316	8,829	14·840	38·9
10	"	Manningham-lane*	"	2·401	28,148	37,108	9,277	14·927	46·3
11	"	" "	"	2·421	failed.	failed.	. . .	14·804	45·0
12	Grauwacke	Penmaenmawr .	"	2·748	40,692	67,572	16,893	13·042	1641·0
13	Granite .	Mount Sorrel. .	"	2·657	. . .	. . .	. . .	13·489	485·3
14	"	" "	"	2·675	51,444	51,444	12,861	13·398	495·0
15	Grauwacke	Ingleton . . .	"	2·787	35,316	(53236)	not crd	12·866	1962·6
16	Granite .	Aberdeen. . .	"	—	27,546	(28340)	not crd	—	—
17	Syenite .	Mount Sorrel. .	"	—	47.284	47,284	11,821	—	—
18	Granite .	Bonaw . . .	1½-in.	—	17,396	24,564	10,917	—	—
19	"	Furnace . . .	"	—	24,564	24,564	10,917	—	—
20	"	A . . .	"	—	22,772	24.564	10,917	—	—
21	Limestone.	B . . .	"	—	17,396	19,188	8,528	—	—
22	"	C . . .	"	—	18,292	19,188	8,528	—	—
23	"	Anston . . .	1-in.	—	2,154	3,050	3,050	—	—
24	"	Worksop . . .	"	—	3,946	7,098	7,098	—	—
25	Sandstone.	D . . .	"	—	3,050	3,498	3,498	—	—
26	"	E . . .	2-in.	—	10,218	12,228	3,057	—	—

On comparing the results of the experiments on the Yorkshire sandstones, it will be seen that the difference of resistance to pressure does not arise so much from the variable character of the stone in different quarries, as from the position in which it is placed as regards its laminated surface, the difference being as 10 : 8 in favour of the stone being crushed upon its bed to the same when crushed in the line of cleavage; the same may be said of the limestones.

Comparing the strengths indicated with those obtained by other experiments, I find a very close approximation in the granites, but considerable difference in the Yorkshire sandstones. Mr. Rennie obtained his specimens from the

* Pressure applied in the direction of the cleavage.

† Pressure applied perpendicularly on the bed of the stone.

same district, the valley of the Aire; but the force required to crush the Bromley Fall stone was much less than that required to fracture similar specimens from the Shipley quarries. The following Table gives some useful results for comparison.

Description of Material.	Crushing Force in lbs. per square inch.	Authority.
Porphyry	40,416	Gauthey.
Granite, Aberdeen . . .	11,209	Rennie.
„ mean of 3 varieties .	11,564	Experiments 14, 18, 19.
Sandstone, Yorkshire . .	6,127	Rennie.
„ mean of 9 varieties	9,824	Experiments 1 to 9.
Brick, hard	1,888	Rennie.
„ red	805	Rennie.

From the above it is evident that there is a considerable difference between the results of Mr. Rennie's experiments and those in the preceding Tables in the case of the sandstones. This may, perhaps, be due to the different methods pursued in the experiments, or from taking the first appearance of fracture as the ultimate power of resistance. Whereas, there is in some cases a difference of nearly a third between the weight required to produce the first crack, and that required subsequently to crush the specimen. This is the more remarkable as all the specimens did not appear to follow the same law, as in some the weight which fractured the specimen by a continuation of the process ultimately crushed it. Experiments of this kind require close observation, and the reason just given may probably account for the difference between Mr. Rennie's and my own results.

All information respecting the strength of materials must be derived from direct experiment, which is always the safest and best guide; and fully aware of the importance of this fact, I have deemed it expedient to append the following list of the bearing powers of some other

materials employed in building, and to which reference may be made in any case where the load is excessive, or where material is subjected to severe strain.

The necessity of these experiments was the more apparent some years since, in the construction of the Britannia and Conway tubular bridges, when fears were entertained of the security of the masonry to support, upon the given area, the immense weight of the tubes, upwards of 1500 tons, resting on one side of the tower. To ascertain how far the material (Anglesea limestone) was calculated to sustain this load, the following experiments were instituted by Mr. Latimer Clarke.

" *Results of experiments made with actual weight on the materials used in the Britannia bridge, January,* 1848.

Brickwork.

	lbs. per square inch.
No. 1.—9-in. cube of cemented brickwork (Nowell and Co.), No. 1 (or best quality) weighing 54 lbs., set between deal boards. Crushed with 19 tons 18 cwt. 2 qrs. 22 lbs.	=551·3
No. 2.—9-in. cube of brickwork, No. 1 weighing 53 lbs., set in cement. Crushed with 22 tons 3 cwt. 0 qr. 17 lbs. . . .	=612·7
No. 3.—9in. cube of brickwork, No. 3 weighing 52 lbs., set in cement. Crushed with 16 tons 8 cwt. 2 qrs. 8 lbs. . . .	=454·3
No. 4.—9¼-in. brickwork, No. 4 weighing 55½ lbs., set in cement. Crushed with 21 tons 14 cwt. 1 qr. 17 lbs.	=568·5
No. 5.—9-in. brickwork, No. 4 weighing 54¼ lbs., set between boards. Crushed with 15 tons 2 cwt. 0 qr. 12 lbs. . . .	=417·0
Mean	521·0

NOTE.—The last three cubes of common brick continued to support the weight, although cracked in all directions; they fell to pieces when the load was removed. All the brickwork began to show irregular cracks a considerable time before it gave way.

The average weight supported by these bricks was 33·5 tons per square foot, equal to a column 583·69 feet high, of such brickwork.

SANDSTONE.

	lbs. per square inch.
No. 6.—3-in. cube red sandstone, weighing 1 lb. $14\frac{3}{8}$ oz., set between boards (made quite dry by being kept in an inhabited room). Crushed with 8 tons 4 cwt. 0 qr. 19 lbs.	=2043·0
No. 7.—3-in. cube sandstone, weighing 1 lb. 14 ozs., set in cement (moderately damp). Crushed with 5 tons 3 cwt. 1 qr. 1 lb. .	=1285·0
No. 8.—3-in. sandstone, weighing 1 lb. $15\frac{1}{2}$ ozs., set in cement (made very wet). Crushed with 4 tons 7 cwt. 0 qr. 21 lbs. . .	=1085·0
No. 9.—6-in. cube sandstone, weighing 18 lbs., set in cement. Crushed with 63 tons 1 cwt. 2 qrs. 6 lbs.	=3924·8
No. 10.—$9\frac{1}{4}$-in. cube sandstone, weighing $68\frac{1}{2}$ lbs., set in cement ($77\frac{1}{2}$ tons were placed upon this without effect, = 2042 lbs. per square inch, which was as much as the machine would carry).	
Mean	2185·0

All the sandstones gave way *suddenly*, and without any previous cracking or warning. The 3-in. cubes appeared of ordinary description; the 6-in. was fine grained, and

appeared tough and of superior quality. After fracture the upper part generally retained the form of an inverted square pyramid about 2½-in. high and very symmetrical, the sides bulging away in pieces all round. The average weight of this material was 130 lbs. 10 ozs. per cube foot, or 17 feet per ton.

The average weight required to crush this sandstone is 134 tons per square foot, equal to a column 2351 feet high of such sandstone.

LIMESTONE.

	lbs. per square inch.
No. 11.—3-in. cube Anglesea limestone, weighing 2 lbs. 10 ozs., set between boards. Crushed with 26 tons 11 cwt. 3 qrs. 9 lbs.	=6618·0
This stone formed numerous cracks and splinters all round, and was considered crushed; but on removing the weight about two-thirds of its area were found uninjured.	
No. 12.—3-in. limestone, weighing 2 lbs. 9 ozs., set between deal boards. Crushed with 32 tons 6 cwt. 0 qr. 1 lb. . . .	=8039·0
This stone also began to splinter externally with 25 tons (or 6220 lbs. per square inch), but ultimately bore as above.	
No. 13.—3-in. limestone, weighing 2 lbs. 9 ozs., set in deal boards. Crushed with 30 tons 18 cwt. 3 qrs. 24 lbs. . . .	=7702·6
No. 14.—Three separate 1-in. cubes limestone, weighing 2 lbs. 9 ozs., set in deal boards. Crushed with 9 tons 7 cwt. 1 qr. 14 lbs.	=6995·3
All crushed simultaneously.	
Mean	7338·2

All the limestones formed *perpendicular* cracks and splinters a long time before they crushed.

Weight of the material from above = 165 lbs. 5 ozs. per cubic foot, or 13½ feet per ton.

The weight required to crush this limestone is 471·15 tons per square foot, equal to a column 6433 feet high of such material.

Previously to the experiments just recorded, it was deemed advisable not to trust to the resisting powers of the material of which the towers of either bridge were composed; and, to make security doubly sure, it was ultimately arranged to rest the tubes upon horizontal and transverse beams of great strength, and by increasing the area subject to compression, the splitting or crushing of the masonry might be prevented. This was done with great care, and the result is the present stability of those important structures.

In conclusion, the following general summary of results, obtained from various materials, shows their respective powers of resistance to forces tending to crush them.

GENERAL SUMMARY OF RESULTS ON COMPRESSION.

	Description of Material.	Crushing force in lbs. per square inch.	Authority.
Iron and Steel	Cast steel		Fairbairn's Experiments on the Mechanical Properties of Metals.—Transactions of the British Association, 1854.
	Blister steel.		
	Cast iron (white, derived from 14 meltings)	214,816	
	Ditto (from 12 meltings) . .	163,744	
	Ditto (from ordinary castings)	89,600	
Stone	Porphyry	40,416	Gauthey.
	Grauwacke, Penmaenmawr .	16,893	Exprmts. No. 12.
	Granite, mean of 3	11,565	Do. Nos. 14, 18, 19.
	Sandstone, Yorkshire . . .	6,127	Rennie.
	Ditto, mean of 9 exprmts. .	9,824	Exprmts. 1 to 10.
	Ditto, Runcorn	2,185	Clark.
	Limestone	8,525	Exprmts. 21, 22.
	Ditto, Anglesea	7,579	Clark.

	Description of Material.	Crushing force in lbs. per square inch.	Authority.
Stone	Ditto, Magnesian—mean . .	5,074	Exprmts. 23, 24.
	Brick, hard	1,888	Rennie.
	Ditto, red	805	"
	Ditto, mean of 4 exprmts. .	1,424	Clark.
Timber.	Box	9,771	Hodgkinson.
	English Oak (dried) . . .	9,509	
	Ash (ditto) . . .	9,363	
	Plumtree (ditto) . . .	8,241	
	Beech	6,402	
	Red Deal	5,748	
	Cedar	5,674	
	Yellow Pine	5,375	

The above summary gives pretty correct data for the guidance of the practical builder in the application of these materials when subjected to a simple crushing force. The experiments might be greatly extended to stone from other localities, but the specimens are of a sufficiently varied character to afford the necessary information to those employed in the constructive arts.

PART II.

LECTURES.

LECTURE I.

ON POPULAR EDUCATION.

THE object I have in view in this address is to direct your attention to certain principles which I hold to be true, and which I consider essential to the development of the human mind, the formation of character, and the right exercise of our duties to society. In the investigation of the all-important question of education, I hope you will give me your attention whilst I endeavour to lay before you such facts as seem to elucidate a subject on which no two men appear to be agreed, and which has occupied the attention of the statesman and philanthropist from the earliest period of our history down to the present time. Notwithstanding the number of treatises that have been written, and the number of speeches that have been delivered, we are still far short of a sound national system of education; and it appears questionable, as society is constituted in this country, whether any system which may be called national would ever supply the wants of the different classes into which the population of the kingdom is divided. Many

of the difficulties which present themselves would be removed if the different denominations of religionists could agree upon a sound system of secular education, supplemented by some general principles of faith to which no real professor of Christianity could object, and on which to build the great moral structure of liberty, honour, and independence. There cannot exist a doubt that the safety and well being, and even the very existence of the state, depends on the education of the people; and our intellectual enjoyments are chiefly derived from the instructions we have received, and the examples which have been set before us, in early life. How essential is it, therefore, that these instructions should inculcate not only the leading truths of natural science, but the great principles of morality by which our future lives are to be governed, and on which depends our bearing towards our families and society at large.

It is not for me to demonstrate what these principles are; they vary according to the system of education that may be practised, and the prejudices which that education may inculcate. Let us, however, be assured that the moral world is governed by the same Great Power as the external creation, from whose determined laws we cannot deviate without injury and danger to ourselves and others. If this be the case, the instructions we receive ought to be such as would teach us to know right from wrong, and how far, through life, our conduct accords with the principles under which our education has been conducted. In this discussion it is not my intention to speak, directly or indirectly, of religious instruction; and although I hold that religious education is essential to the well being of society, I nevertheless leave all matters of belief to the discretion of parents, as regards the principles upon which their children should or should not be educated.

What we have to treat of on this occasion is the charac-

ter of training a young man should receive, whose only inheritance is a sound mind and a strong constitution, in the various stages of his early life, and how his powers should be cultivated for his own happiness and the benefit of those with whom he has to live. Viewing the subject in this light, it will be necessary to divide it as follows:—

1st.—*Elementary Teaching and Physical Training.*

It has been rightly observed that a sound foundation is essential to a secure superstructure; and this truism applies as forcibly to the development and cultivation of the human mind as it does to material constructions.

What should therefore first engage our attention, from infancy up to five years of age, is to nurse and encourage the growth of the body, to strengthen the muscles, and thus to establish a sound foundation for the higher powers of intellect by ensuring to the recipient a vigorous and hardy constitution. During this period the mind receives impressions as a child, which in after life will influence its conduct as a man; and very much will depend upon the mother, or those that have the care of infancy, that these impressions be of the right sort, and that they have a direct tendency to virtue, and those dispositions of character which influence the future fortunes of the man. In this early stage of what can scarcely be called tuition, but which nevertheless forms the nucleus of a system, it must be borne in mind that a healthy body is the twin sister of a sound mind, and that any neglect or injury to the former is sure to affect the latter, and weaken the powers we are anxious to cultivate. In future developments, how much therefore depends upon the mother, and how very important it is that we should have good mothers possessing all the qualifications necessary to bring up their children, and prepare them for the reception of those

principles we are desirous they should inherit in after life. This impression suggests the all-important question of the education of women; and on this point I shall have to trouble you with a few observations.

I have already stated that our earliest impressions, whether for good or evil, are received from the mother. Almost every child is endowed with amazingly quick powers of imitation; it is moulded and impressed by its earliest associates, and when the influence and example of a prudent and discreet mother predominates, the fruits of a sound judgment and a well spent life are almost sure to be forthcoming and ripened to maturity. Hence it becomes a question of deep interest to the well being of society that the first step in our educational career should be applied to the softer sex, in order that our minds may derive from that source the germs of correct mental culture and desires that tend upwards to honour and to virtue. Much may be said in illustration of the education of females; but the subject is one of difficulty, and requires the most careful consideration, in devising a system which shall harmonise with the feelings of the sex, while it strengthens the understanding and cultivates the affections of the heart.

It has been stated that the female mind is not equal to, and cannot realise, the sterner duties of the male. This appears to be a mistake, as we find that the minds of women are not only susceptible of large development, but for penetration, quickness of perception, and high attainments in mental culture, they are fully equal, if not superior, in some cases, to the active and more rigid characteristics of the other sex. These qualifications stand prominently forward in the acquirements of the female writers of the present day; and to the credit of the sex we may instance as examples the works of Mrs. Somerville in science, and those of Miss Evans, Mrs. Gaskell

and others in the leading walks of fiction and polite literature.

Again, we find in the female mind a degree of aptitude and fineness of touch in works of precision, that we almost look for in vain in the labours of man. The patient submission to daily toil, the untiring energy, and minute accuracy of the seamstress is proverbial, and in all the lighter descriptions of labour, such as watchmaking, sewing, weaving, &c., women are found to be better qualified than men. In commercial transactions the same steadiness of action, patient endurance, critical attention to minutiæ, is observable in women; and the duties of the bureau, counter, and book-keeping are performed by women with a degree of exactitude in France that is enough to put their partners in life to the blush. All these duties are done by women, and they are well done, during a period in some cases when their husbands and sons are in the café or at the billiard-table.

But of all other occupations, woman is seen to most advantage in the domestic circle—in the management of her home and the education of her children. It is here where the mother becomes the instructress, the example, and the *glory of her family;* and it is to these duties, be she rich or poor, that the affections of the heart should be moulded, and the faculties of the mind should be trained. This species of culture should form a part of our national system, and the education of the sex should never be left to chance, but they should be taught from early life the value of time in the efficient and honest discharge of their domestic duties.

Much has yet to be accomplished in this direction before we can calculate upon raising up for the service of man a phalanx of good and virtuous mothers, endowed with all the finer feelings of their nature, united to a large stock of *sound common sense.*

2nd.—*From the Age of Five to Ten Years.*

At this age we may safely commence a system of preparatory instruction in reading, writing, and arithmetic; and supposing the child endowed with a healthy frame and clear intellect, he will, in the course of that time, have mastered the ordinary rules of arithmetic and have acquired a taste for reading. In this stage of progress I would observe that much will depend upon the books selected for instruction. In my opinion they should amuse as well as instruct; and those containing stories of animals and narratives of individuals will be the most acceptable and attractive to the growing intellect of the child. Tales and descriptions of this kind will give him a taste for books, and a pleasure in their perusal, which he will not lose in riper years. It is astonishing what may be done with children at a tender age. Their powers of imitation, love of play, and all the endearments of life, are in a high degree attractive; and much will depend upon the parents, the mother in particular, as to the class of instruction that should be followed, whether on the domestic hearth or at school. I am glad to observe that the system of tuition is greatly improved since my time, and that the school books of the present day are more attractive and better adapted to the capacity of the child than at any previous epoch in the history of our educational system. From fifty to sixty years ago, Barrow's Collection, the Bible, and Dilworth's Arithmetic, were the only books in use, and in case of any dulness or want of comprehension, the boy's intellects were enlivened by an application of the most sensitive description, so much so in fact as to bring tears into his eyes. This was a general practice in those days, and I well remember what was called the clearing day, which took place every Thursday, when our accounts were settled for the

week, by the mistaken idea of attempting to force in at the extremities what was unable to penetrate into the more noble and more intellectual part of the system. It is fortunate for the present generation that a more merciful system of management has been introduced, and that the schools of the present day are much better adapted for the cultivation of the minds of youth than at any former period when measures of much greater severity were adopted. It will not be necessary to enlarge upon this division of the subject farther than to observe that at this tender age it is essential to the future happiness of the child, and his usefulness in after life, that he should be kindly treated, and that upon a system calculated to develope his latent powers, and prepare him for a higher and more extended sphere of instruction. These are my views in regard to the early stages of training; and although there is a difference of opinion as to where and in what manner it should be given, I am nevertheless convinced that it should be received at a public school.

3rd.—*Education during the Period intervening between the Age of Ten and Fourteen.*

Assuming our views of infant education to be correct, we are now arrived at that stage of probationary existence, when the boy begins to think something of himself, and with feelings which deepen into manly independence he discovers a power which he considers peculiarly his own, and which he is unwilling to trust in the hands of others. This feeling should never be suppressed, but carefully watched and modified in cases where it tends to encroach upon the rights of others. In a public school it generally brings its own corrective; and in this little republic there are those both able and willing to control the turbulent and self-willed intruder. To the agricultural

labourer, the mechanic, and the artisan, this is a time of vital importance, as at this period may be laid the foundations of future comfort, success, and renown. I do not mean by these observations to say that every candidate for honours in his particular walk of life will succeed; on the contrary it is only a few amongst the many that attain distinction. Yet the prize is worth looking after; but unless the taste for knowledge, and the power to apply it be there, it is vain to think of ascending the scale in the great contests of human existence. I speak from experience of these matters; and I can assure you it is a long time since I discovered that nothing valuable was to be attained without study, in the first instance, and constant labour and application in the second. It is, therefore, important that the boy should never lose sight of the object he is striving to attain, and that his mind should be directed to those points of study that are likely to stimulate him to action in the full and faithful discharge of his duties in after life. At this period, whilst the mind of the pupil is receiving the rudiments of a plain but useful education, care should be taken to ascertain the peculiar bent of his mind, and to encourage tuition in those branches best suited to his taste, and best adapted to the circumstances of his future entrance into life. This is the suitable time to give instruction in grammar, history, biography, arithmetic, geometry, and practical mathematics. All these may be taught with advantage, leaving subsequently to the pupil himself the choice of a profession or trade, in which the knowledge he has acquired can be usefully and properly applied.

Towards the end of his educational course the boy, if he be aspiring, assumes something of the character of the man. He begins to assert the dignity of his nature, and looks out for that description of employment by which he can maintain himself. This love of labour in early life is characteristic of

the youth of this kingdom. And here I cannot do better than reiterate a part of the speech of the Right Honourable Sotheron Estcourt, the chairman of the Poor Law Board, who, in his address to the members of the Hants and Wilts Adult Society, speaking of the difficulty of attaching young persons to educational pursuits, he said that, "in his desire to remedy certain evils, he was persuaded that anything like an attempt to catch hold of young men and young women after they leave school, and by holding out either a pecuniary reward, or in any other manner attempting to persuade them to take a deeper interest in the subject of education than their own minds naturally induce them to take, will end in failure." And in confirmation of the truth of these observations he further observes, "that it is rather too much to expect that an employer will consent to keep a boy at school when he ought to be at work; and, indeed, even in that case he doubted whether such a plan would be successful. He could give an instance in which it was not. Some years ago he was very desirous of doing something of the kind in his own parish, and engaged two boys to do a certain amount of work; but he made an engagement with them that he would not pay them unless the boy who was not employed in labour attended the school. He, however, totally failed, for the boys preferred labour to school, and both of them left his employment as soon as they could find others to give it them. He attempted to interfere artificially with their natural desire, and deservedly failed." Nothing can be more true than the above observations; and the question is, how to deal with this innate preference for labour so as to make it productive of good to the individual and beneficial to the community. In the solution of this question I hope to show that much may be accomplished in the next division of my subject, viz.—

4th.—*Adult Education from the Age of Fourteen to Twenty.*

This stage of intellectual culture is probably the most important in the whole scale of mental progress. At this time the wild passions of youth have to be controlled and brought within the bounds of moderation, and at this period scholastic instruction ends, and self-culture begins. This is a period of vital moment to youth, when a life of labour should be relieved by study, having for its object the acquisition of knowledge based on professional pursuits, and calculated to enlarge the faculties of the mind. It is astonishing how much a young man may gain in this way without the guidance or assistance of any teacher whatever. I will give you an instance from my own experience. I had to teach myself, and that without the aid of either tutors or mechanics' institutes, by a course of reading and practical mathematics, which I pursued from sixteen to twenty-four with unrelaxed avidity after the labours of the day were over, and which not unfrequently encroached upon the hours of sleep. I subjected myself to this system of self-teaching for five days in the week, devoting the remainder to pleasure and amusement; and now at this advanced period of life I find myself nothing the worse, but all the better for it. I will not trouble you with further examples, but proceed to state what course I consider necessary to be pursued in aiding the progress of a youth in mental culture during this early period of his career. We ought, in my opinion, to afford a *knowledge of natural science in connection with labour and the professional pursuits* in which those we teach are engaged. A youth may be a mechanic, an artisan, or an agricultural labourer, or he may be a soldier or a sailor; it is all the same, whatever his professional pursuits may be, they involve certain duties, and these cannot be properly executed

without a knowledge of the laws upon which they are founded. To become an expert workman in any handicraft employment is not entirely the work of the hand; on the contrary, the head is the director of every movement, and to effect these skilfully he must possess a knowledge of the laws which the Almighty has so intelligibly and so beautifully written upon the page of nature. A labourer in the field cannot cut a drain or turn up the soil by the spade or the plough without having some perception of the objects of his toil. An artisan cannot weave a piece of cloth, nor a mechanic execute a piece of machinery, without some consideration of the principles on which these operations are conducted, or what I call the physical truths of construction, applicable in every case as fixed laws to the operations of man. Nor can a soldier or sailor, in the defence of his country, adequately exercise the functions of his profession without some perception of the great laws by which the arts of attack and defence are governed. It is in the knowledge of these physical truths that we shall exercise our varied pursuits with most benefit to ourselves and most advantage to the community; and these should therefore form a part of every man and every woman's education. Yet in recommending the study of natural laws bearing upon the duties of life, it is not my intention, nor is it my desire, to institute a nation of philosophers, but only to instruct the rising generation of men and women in the more efficient discharge of their respective duties, and more particularly with a clearer apprehension of the unerring laws by which every operation of the human mind is governed, whether in the physical or the moral world. The economy of nature should therefore form a part of every man's instruction; and we shall best discharge our duty to the rising generation by imparting to our successors that knowledge which leads to nature and to nature's laws.

In the preceding remarks I have endeavoured to trace the culture essential to the development of character from childhood to the age of puberty, in the case of a young man whose parents are poor, and who is entirely dependent for subsistence on his own talents and self-reliance. A young man so placed is in a position calculated to awaken within him resources which in more favourable circumstances might have lain dormant. He might, in affluence, go through life in a quiet unostentatious manner, highly respectable, no doubt, but wonderfully deficient in energy compared with those whose characters are marked by their labours, enterprise, and contributions to the general stock of knowledge. In fact such a man, beginning the world with self-reliance alone, is in a condition, independently of other circumstances, to work out his own fortune with a certainty that we seldom meet with in those more favourably placed.

Poor Richard, in his almanac, says that "God helps those who help themselves;" and, bearing this truism in view, a man has nothing to lose, but everything to gain, by a life of laborious and active industry. Where his inclinations and habits tend in that direction, he is sure of encouragement and assistance, and there is no difficulty in finding those who are both able and willing to lend a helping hand to one whose mind is imbued with an honest ambition. To one of well regulated mind there is no pleasure so great as to witness the persevering energies of youth labouring against difficulties in the pursuit of knowledge. On such occasions most men are ready to encourage the development of an intellect on which the future career of the man is already forcibly and strongly marked.

Let us follow historically the leading events of the life of such a man,—a man who has risen by the force of his own talents to distinction, and has been appreciated as a benefactor of his species. We have many men of this kind, for it

is only under a free government, where the necessary facilities for progress are at hand, that such men can flourish. We may rest assured that such a position has not been attained merely by aspiration; on the contrary, nothing valuable is obtained without exertion, and to ensure success there is nothing for it but indomitable and never-relaxed perseverance. If you accompany such men as Ferguson, Franklin, Watt, or Stephenson, in their intellectual progress, you will be at no loss to discover the secret by which they attained to greatness. They also had to contend with difficulties in early life, but a laudable ambition and an untiring perseverance overcame every obstacle, and their victories over their early impediments were the harbingers of their ultimate triumphs.

To rise in the world three qualifications are necessary: truthfulness, a sound judgment, and persevering industry.

I am of opinion that no man can permanently advance himself without strict honesty of purpose and adherence to the principles of truth; then in the exercise of our professional, as well as of our domestic duties, a clear perception and a sound judgment are necessary to guide us in the right direction; and, lastly, an unwearied perseverance, superadded to these qualifications, seldom fails to ensure to its possessor certain success.

Some may think they have no chance, that no opportunity of distinguishing themselves offers itself; but this I do not believe. I can more readily conceive that they have not sought an opportunity, nor availed themselves of it when fortune has thrown it in their way. It is of no use standing and calling upon Jupiter for help, when we should energetically and at once put our own shoulder to the wheel. To improve our condition in life we must seize opportunities as they occur, and to do this we must have prepared ourselves by the faithful and honest discharge of our ordinary duties.

In the early stages of a man's life—I am speaking now of a working man, who has everything to gain and nothing to lose—it is necessary that he should carry on his education along with his trade; and I would recommend him, without a tutor, whom I assume he would be unable to pay for, to persevere in a course of instructive reading in connection with the trade he has to follow, and one calculated to make him an expert workman and a useful member of society. In recommending these studies, I am not one of those who would impose a rigid observance of duties, which, to be profitable, must be agreeable, but perseverance for a time, until the requisite elementary knowledge has been attained, will make further study attractive. Young people require relaxation, and he would be a hard preceptor indeed who would deny to them the enjoyments suitable to their age, as friendships and associations formed in early life give to later years their happiest and most attractive reminiscences; and I hope the good sense of the people of this country will always preserve them from influences inimical to the innocent amusement of their leisure hours. The excesses of pleasurable enjoyment must, however, be guarded against, and on every occasion made subservient to the duties of life.

Let me draw your attention to the position of a young man of fifteen or sixteen years of age, thrown on the world with no other means of subsistence than a robust constitution, an active mind, and the rudiments of a plain education, such as reading, writing, and some knowledge of arithmetic. Let us suppose the means of learning some handicraft trade within his reach, and that he thus obtains some small weekly wages sufficient for his maintenance. Thus placed, with an active mind, a stout heart, and an indomitable perseverance, he begins life with many advantages; the necessities of his position will call forth energies unknown to him before, or to those better provided for, and

the pleasure of overcoming difficulties is an encouragement to action, and renders sensible those qualities of character which otherwise might have remained latent. These are positive advantages, and many a young aspirant who laments his misfortunes in being thus left to his own resources, sees only the dark side of the present, whilst the future is looming in the distance with a flood of light. Is not then the prize of distinction worth contending for? Is it not a question for every young man in the circumstances I have described to consider whether he will undertake the task, and not only commence, but pursue, a course of study calculated to win for him a more honourable station in life?

At a time when both mind and hand are under training, it is desirable that the self-teaching student should pursue his studies methodically, and not waste his time in vacillation. He must bear in mind that time is the ever-flowing stream on which he floats to the scene of his future labours. He must, as the Scotch say, "put a stout heart to a stay brae," and never lose sight of the object he wishes to attain; he will then make provision for leisure hours by a course of arithmetic, geometry, and mathematics, and an equally useful course of chemistry and physics; and for general reading he could not do better than study some of our best authors, such as Addison, Hume, and Goldsmith of the last century, and Scott, Prescott, and Macaulay of this. In addition, he may enrich his mind with some of our best poets, beginning with Shakspeare, Burns, and Byron, Southey, Scott, and Tennyson. All these may be read with advantage, and interspersed with the newspapers and periodicals of the day, will lay the foundations of future usefulness in the more active scenes of life.

Having thus carried the young aspirant over a period which may last from fifteen to one-and-twenty, he then

presents himself to the world with a trade in his hand and a mind fully prepared to act an important part in life. Such a person will not be long without employment, and his previous discipline will have fitted him for the tasks he has to perform. He respects his employer, and endeavours to discharge his duty with honesty and alacrity; in a few years he gains his master's confidence, becomes his assistant, probably marries his daughter, and settles down as the father of a family and a respectable tradesman for the remainder of his days. In such a career there is honour and comfort, and provided his mind is not poisoned and his independence destroyed by unions and trade clubs, he may calculate on a prosperous life and a respected old age.

A settlement by marriage with encouraging prospects does not close a man's education: *that indeed he does not finish till he dies.* We are all scholars and always at school from infancy to the decrepitude of old age. But a settlement in life is doubtless the beginning of a new era, another stage in our preliminary journey, and along with it come numerous and important duties, which it is expected we shall duly and honestly fulfil. Every new phase in our existence brings new responsibilities, and entails a constant and growing necessity for extended knowledge; and provided we are desirous of making ourselves useful in our day and generation, we must labour first in the acquisition of knowledge, secondly in its application, and lastly, we must constantly strive to attain a life of spotless integrity.

In conclusion, I have to observe that we have much to be grateful for in the many excellent educational institutions of which this country at the present time can boast, and the great facilities now afforded to all in the attainment of knowledge at the merest modicum of cost. Compare the present with the times I have alluded to, and you will find that your fathers had not the advantages you possess. In my own time there were no mechanics'

institutes, no cheap publications, no free libraries, and comparatively little encouragement given to education. In those days we had to borrow books from those who would lend them, and he was a happy youth indeed who found amongst his father's friends and acquaintances one who would encourage and support him in the pursuit of knowledge. Learning was then considered a dangerous thing, and many went so far as to say that education would be the ruin of the poor and the annoyance of the rich, making them discontented with their lot in life, and paving the way to rebellion and insurrection. Now we have lived to see the falsity of this doctrine, and I trust we may yet live to see the labouring man combine with his daily pursuits the blessings of a mind free from prejudice, but full in the enjoyment of intellectual culture.

LECTURE II.

ON THE MACHINERY EMPLOYED IN AGRICULTURE.

Research into the annals of antiquity throws but a feeble light upon the methods adopted by primitive nations in the tillage of the soil; or upon the implements employed in procuring the products of agriculture and converting them into food. The earliest accounts upon which reliance can be placed are those in the sacred Scriptures, whence we learn that the Babylonians and Egyptians were rich in agricultural resources, and that the labours of the husbandman on the banks of the Nile and the Euphrates were rewarded by returns of "sixty, seventy, and one hundred-fold." This large return was, doubtless, the result, partly of the fertility of the soil, which received year by year, on the overflowing of the rivers, deposits which enriched the soil; and partly also of the favouring influence of an almost tropical climate.

It is a mistake to suppose that the farmers of these remote times were unacquainted with the simpler implements of agriculture, for even at the present day there remain enduring records of such instruments in the paintings on the walls of Egyptian temples, and on the sculptures and coins of later date. Most of our agricultural implements may be traced back to an ancient origin, and it is more than probable that the Egyptian farmer of nearly 3000 years ago had many of the conveniences of the dwelling-house and well stocked farm-yard that may be seen in our own homesteads at the present day. Such facts as these

should make us cautious in assuming to ourselves the merit of original invention and improvement, when history furnishes such unmistakeable records of the great antiquity of machines of similar descriptions.

To another very ancient race, the Egyptians and Romans, as well as ourselves, were probably indebted for the discovery and application of many of the machines by which we cultivate the soil. The very people with whom we are now prosecuting a deadly feud* are the descendants of that race to whom we owe some of the most important aids in the cultivation of the soil, and judging from the traditionary annals of the country we may conclude that the inhabitants of Hindostan and Central India were amongst the earliest to improve the art of tillage, and to introduce that system of rotation, by which the soil is enabled to produce larger and more abundant crops.

Like most other nations the Greeks were at first rather a pastoral than an agricultural people, and although Hesiod and succeeding writers have left records upon the subject, we are less acquainted with the progress and extent of agriculture in Greece than in Italy, or almost any other country.

Amongst the Romans agriculture was regarded as one of the most important and profitable pursuits, and during the earlier days of the republic it engaged the attention of the bravest citizens and most skilful generals. And, no doubt, in Italy agriculture owed much of its successful progress to the energies developed and disciplined in the sterner school of war. The Romans were well acquainted with irrigation, manuring, ploughing, draining, and other more obvious processes connected with the fertilisation of the land and securing its products.

* Written immediately after the revolt of the native army in our Indian possessions in 1858.

During the middle ages agriculture, no longer considered an honourable occupation, sunk in most countries to the lowest possible condition. The processes of irrigation and manuring were neglected, or lost, and hence it is not surprising that under such a system the products should not be much more, according to Humboldt, than four times the quantity of the seed sown.

In America, during the paternal reigns of the Incas of Peru, agriculture was carried on with great success by that ancient and intelligent people; and until overrun by the Spaniards under Pizarro they maintained their character as a civilised community, subsisting on the products of the soil, which they cultivated upon principles superior to those known in Europe at the time, and in other respects conducive to the interests and well being of the people. The Peruvians were well acquainted with the value of *guano*, which, according to Prescott, was procured from the coast, and was held in such high estimation that no person was permitted, under risk of severe penalties, to disturb the penguins on the islands during the time of breeding. Again, their system of irrigation was upon a magnificent scale, the water being carried across valleys and round the sides of mountains to an extent far exceeding works of a similar nature in modern times. All the lessons to be derived from these undertakings were lost upon the Spaniards, by whom the Peruvians and their works were alike neglected and destroyed.

In this country the cultivation of the soil was little studied as a profession, and very imperfectly practised up to the middle of the last century. Up to the union of the kingdoms of England and Scotland the crops of corn are very small in comparison to what they are at present; and wheat must have borne a small proportion to the inferior descriptions of grain, such as oats and rye, with probably some occasional patches of beans and barley.

Potatoes, carrots, turnips, &c., were unknown, and it is recorded that during the reign of Henry VIII., if a salad was wanted, messengers had to be sent to Holland and Flanders for it. Contrasting the mode of living in those days with the abundant luxuries which are now within our reach, and the comparison is immeasurably in favour of the times in which we live.

From the commencement of the last century to the year 1760, agriculture gave little or no indication of progress, and it was not till that time that a movement took place either in the culture of the soil or the management of live stock. From that period, however, may be dated the first step towards a system which has brought the greater portion of the surface of these islands into cultivation for the sustenance of our growing and greatly increasing population.

It is to the southern and eastern parts of Scotland, and to a few distinguished men of the southern part of the United Kingdom, that we are indebted for these early movements; and it is no insignificant compliment to our countrymen to say that they were the great pioneers in the improvement of agriculture. Among the earliest and most distinguished of these we must not forget the name of *Arthur Young*, the father of English farming, and one of the most sagacious and talented of men. As a contemporary and colleague he allied himself with the eccentric but gifted Robert Bakewell, the founder of the breed of Leicester sheep, and the yeoman-farmer and systematic breeder of live stock. Bakewell was the very ideal of an independent English farmer; his house was his castle, and he used to sit under a huge chimney, clad in a brown coat, scarlet waistcoat, leather breeches, and top boots. There he sat, the model of independence, the head of his family, and lord of his domain. He breakfasted at eight, dined at one, supped at nine, and whoever was there, though at

times he entertained princes and royal dukes, he knocked out the ashes of his last pipe and to bed at eleven. I mention these things as instancing the native vigour and independence of a real English farmer, and I recommend him to you as a model worthy of imitation.

Our progress since the times of Bakewell has been rapid and steady, and has placed us in the first position as agriculturists among the nations of the world. A distinguished writer on the progress of agriculture says that, "two years ago, a few Englishmen accepted an invitation of the French government to exhibit in competition with the picked agricultural and mechanical skill of continental Europe, and found themselves," as he truly observes, "by a long interval, *first* in the arts and sciences required for producing meat and corn in the most economical manner under a climate not eminently favourable, and on land which has lost its virgin fertility." He further observes that, "the live stock of the British Islands are distinguished for three merits,—the early period at which they become ripe for the butcher; the great amount of food they produce in return for the food they consume; and the large proportion of prime meat that they yield."

The machinery and implements employed in agriculture, to which it is my immediate object to direct your attention, are thus spoken of by the same writer: — "The implements of England are distinguished for solidity of construction, simplicity of details, and economy in price, as well as for the rapidity and completeness with which they execute their work." Now in this eulogium on English skill, I think we are all agreed, and so far as I can judge from a careful inspection of the different implements, we shall have to trace our errors and defects in tillage not to them, but to ignorance, indolence, or, what is too often the case, want of capital on the part of the farmer to ensure their application.

Three conditions appear to me to be requisite to ensure complete success, in the cultivation of the soil, assuming that the requisite capital is forthcoming to stock and work the farm.

1st. A never tiring industry, and an indomitable perseverance in farming pursuits.

2nd. A practical knowledge of the chemistry of agriculture as regards manures, composts, the nature of the soil and substrata, and the treatment to be pursued in rotations to secure an increased fertility.

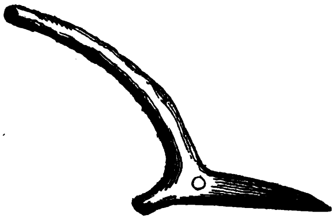
Lastly, the application of machinery, calculated to work the farm in the best manner and at the least possible cost.

In making these statements I am probably treading on dangerous ground, and you will naturally question my authority in presuming to lecture you in this manner. It is true that I am not a *farmer*, but I have arrived at these conclusions from a long experience of the benefits derived from the application of science and the introduction of machinery in other professions; and if I have ventured on this occasion to step out of the way for a purpose in which I hope to make myself useful, I trust you will take the will for the deed, and bear with me while I endeavour to describe objects with which I am more familiar.

The early tools of the husbandman were probably of the rudest and most simple description, and the first which would naturally suggest itself to our forefathers in the dawn of civilisation, would be the branch of a tree which might answer the part of a spade or a hoe for loosening the soil. After an instrument so primitive and simple would follow an attempt at the plough, formed of the crooked branch of a tree, as in the annexed sketch, and drawn by men or oxen through the soil. In fact, some ploughs employed at the present day, in some remote districts of the continent of Europe, are of the same primitive description, simply consisting of a block of wood as a handle, without a

coulter, and with a wooden share, sometimes shod with iron and sometimes not. Another step in advance would be when an iron share and coulter were added to an instrument of such primitive construction.

Fig. 27.



Ploughs composed entirely of wood, excepting only the coulter, share, and a few strips of iron on the mouldboard, were in universal use up to the middle of last century. Since then iron has supplanted the wood, and now is in most cases the only material employed in its construction; and we are mainly indebted to the Scotch for the introduction of this material in the manufacture of this important implement.

One of the best and lightest instruments of this kind is the Scotch swing plough, which is frequently under 2 cwt., or about 210 lbs. in weight, and is worked by two horses. The Lanarkshire plough is different from the above, making a trapezoidal instead of a rectangular furrow, but in other respects they are nearly the same in form and character.

In England most of the ploughs are made with wheels in front, and are drawn by two or sometimes three horses. This system requires an additional driver, and it is very questionable if the work is so well done as by a good

ploughman and pair of horses with the Scotch form of plough. Such, however, is the force of habit and the attachment to old tools and old customs, as to encourage the prejudice against any innovation on the slowly declining methods of ages that are past. Be this as it may, it is quite clear that the introduction of the improved iron plough, which like the *Minié rifle* in the army has superseded the clumsy *brown Bess* of agriculture formerly in use, and has been to the farmer a most important and advantageous change.

Other machines of which I wish to treat are so numerous and important that I shall have to pass over many essential to high cultivation. Good implements are the twin-sisters of good cultivation, and the latter cannot be secured without the former. Such implements are harrows, cultivators to stir up and loosen the soil, grubbers to gather weeds, drills, distributors, clod-crushers, and rollers. All these machines should be part of the farmer's stock, and cannot be dispensed with. It is absolutely necessary in the present improved state of our knowledge, and with our present demand for agricultural produce, that a well conducted farm should have all the machinery necessary to carry out the new system of management, and so save time and labour in all the varying operations of husbandry. The description of all these implements, however, I must leave to abler hands than my own, and refer you to Stephens' *Book of the Farm*, and similar agricultural writings, where you have the recommendations of practical farmers, and of men of high standing and authority in their profession.

To every intelligent observer interested in the progress of agriculture, it must however appear evident that we are at the present time in a state of transition, and that the epoch is fast approaching when a total change is likely to be effected in the cultivation of the soil; steam, the great innovator, having effected revolutions in almost every

branch of human industry, is now invading with irresistible force the province of agriculture. The farmer may object to and oppose the change, but he cannot prevent it, and he must, in my opinion, ultimately succumb to the necessities of an increasing population and the onward progress of the arts.

The first step in preparing the land for the reception of the seed is the disintegration of the soil, or the loosening and turning over of the mould to a depth sufficient to admit the air and to allow the roots of the plant to penetrate, in order to ensure its necessary support and supply of food. To attain these objects, it is found from long practice to be absolutely necessary to carry off by an effective system of drainage the superfluous water, and by these means to allow the rain to percolate through the soil, the surplus being passed into the drain and only the requisite quantity of water retained for vegetation. The number and direction of the drains must be left to the farmer, who will be guided by the nature of the subsoil and the position of the field to be drained. The depth to which the drains should be cut is also a consideration of some importance. Mr. Smith of Deanston recommended 2 feet 6 inches to 3 feet as the proper depth, but it has since been found necessary to go as deep as 3 feet 6 inches or 4 feet in order to protect them from injury and increase the easy flow of water to the outlets. To accomplish this increase of depth in the soil the subsoil plough was invented, and we are indebted to Mr. Smith of Deanston for the introduction of this very valuable and important implement. It is used in almost every description of ground that admits of subsoiling, and in some cases, when the bottom is a stiff clay, four or six horses are required to loosen the subsoil, and ultimately to convert it into a fertile and productive mould.

Some improvements have been made on this plough,

but the principle on which it was first constructed has not been altered since its introduction.

To return from this digression on draining to the employment of steam. It will be in the recollection of every one present that less than a century ago the machinery for spinning flax and cotton was confined to a single wheel and spindle, and the produce was limited to what could be effected with such an instrument by the human hand. Now the number of spindles employed are counted by hundreds of thousands instead of by thousands as then, and instead of working one spindle apiece, one person now works a thousand. A change of similar character and extent may yet be in store for the farmer; he would be a bold man who in these days of change and progress would stand forward and say that we had arrived in any art at the final stage of human improvement, the ultimate goal of human progress. My opinion is that in agriculture especially, so far from being perfect, we are in a state of transition, and that it only requires the willing co-operation of the agriculturist and engineer to establish a new era in the history of the machinery of agriculture.

Let us, for example, look for a moment at what has been done and is doing towards the introduction of the steam plough. Steam power having already been applied to the millwork of the farm in threshing, grinding, slicing, chopping and cutting, it is not unreasonable to suppose that the same application may be made in the field in the more laborious operation of breaking up the soil and preparing it for the reception of the seed. Mr. Hoskyns, in his admirable treatise on the clay farm, states that preparatory tillage consists in the comminution, aëration, and inversion of the soil, all of which he considers proper to effect by a properly formed machine at a single operation, and he is of opinion that, *that* machine should be a "*revolving cultivator.*" It is difficult, however, in the present

state of our knowledge to say which is likely to prove the best and most efficient machine for effecting these objects.

At an early period of my own history I made a model of a vertical steam cultivator, or a digging machine with three spades intended to be propelled by steam, and cutting to a depth of ten to twelve inches. The spades were worked by cranks and slides from the engine, and the boiler cylinders and other works were supported on a large cast-iron roller and front wheel, which were moved forward by the engine on the solid unbroken ground at a rate of speed due to the action of the spades: these were suspended on a frame on one side of the machine, and turned over the cuts as they were delivered by an inclined plane or projecting *cam*, which gave them an obliquity of motion in their ascent from the ground after taking the cut. This machine I had the honour to exhibit, in 1813, at the Society of Arts and Manufactures, and the then existing Board of Agriculture, where, I believe, it may yet be seen.

From that period up to 1839, when Mr. Henry Parkes proposed compressed air, or a vacuum, as an auxiliary for conveying motion from a stationary engine to travelling instruments fixed on a carriage, nothing of moment had been done; and it is only recently that a movement has been made in that direction.

Mr. J. Algernon Clarke, in his paper upon "The Application of Steam Power to the Cultivation of the Soil," states that, "for making the steam engine itself an agricultural locomotive we have Mr. Boydell's endless railway engine, and the traction engine, which was exhibited at the Salisbury Agricultural Meeting. It was proved that it could climb considerable gradients; but taking the weight of the engine with its water and coal into consideration, I should question whether the suggestions and improvements of *Tuxford*, *Hall*, and *Smith* are

ever likely to overcome the difficulties of rough surfaces where so much of the power is expended in carrying the engine itself forward over steep and unequal ground."

To overcome these difficulties, I apprehend we must make the engine with a succession of fixtures along the headlands, and have recourse to a windlass, or movable pulley and rope, in order to compass the tillage of hilly or unequal surfaces. This, I am persuaded, may be done with economy and effect by the introduction of a suitable engine and guide-pulleys made movable along the headlands. By this arrangement the whole power of the engine would be applied to the ploughs, and the friction consequent upon the drag of a considerable length of rope.

Mr. Fowler has adopted this system, and, according to returns received, it is stated that "the working cost of deeply breaking up the soil at five acres per diem, including the shifting of the tackle, is *5s. 2d.*; and of trenching and subsoiling, three acres per diem, *8s. 8d.* per acre; the wear and tear being taken at *1s. 6d.* per acre more. The price of the tackle and implements adapted to a common portable 7-horse engine is *220l.*, and the experience of several farmers appears to show that it is worth while to lay out this sum in order to derive full benefit from the process." Mr. Smith of Deanston's method of turning the instrument at the end of its course is by simply having it yoked to the ropes by a turn bow or hook in front, an exceedingly simple and ready arrangement.

Mr. Clarke, in his paper, states rightly that the best and indeed the first plan ever brought into actual operation is that of the engine and head gear on one headland, and an anchorage and pulley on the other, both being shifted along as the work proceeds. This is Mr. Fowler's plan, and is that which was exhibited at Stirling, where six and three-quarter acres were ploughed to a depth of

five and a half inches at an estimated cost of 8*s.* per acre, which by horse labour would have cost 15*s.* per acre. On milder soils seven inches deep at the rate of nine and a half acres a day cost 6*s.* an acre, which by horse labour would have cost 8*s.* per acre. The trenching implement going twelve inches deep, ploughed at the rate of five acres per day at a cost of 11*s.* per acre, which would require six horses in order to accomplish one acre per day.

The saving may therefore be reckoned to be 35 per cent. upon loamy land; 40 per cent. upon heavy land, and 60 per cent. in the trenching process.

Such are the statements Mr. Clarke has given in his paper, and assuming these returns to be correct we may safely look forward to increased improvement and great diminution of cost in the process of steam ploughing.

Again, referring to the experimental trials at Stirling, I must not forget to notice the superior quality of the work done, and the great advantage derived from turning over the furrows at a rapid motion, thus dispensing with the consolidating effects produced by the horses and other damaging agencies affecting the soil as it leaves the mould board of the plough. On this principle it will be observed that only 800 yards of wire rope are required for ploughing 400 yards of furrow, and the price of the entire apparatus for a 7-horse engine does not exceed 280*l.* The hands required are only two men and three boys, exclusive of water carriers.

Numerous suggestions have been made in regard to the above process, and I may be allowed to observe that what is wanted is *not* several ploughs attached to the drag rope and guided by hand, but a series of ploughs fixed in a frame or carriage with wheels, susceptible of being guided in a straight line at a uniform depth from the surface over which it is moved. A machine of this sort with the

ploughs tilting upon a centre and ploughing both ways is adopted by Mr. Fowler.

On this subject, Mr. Clarke observes, that we can imagine no better plan than that of balancing two sets of fixed ploughs upon a single pair of wheels. The frame being hung midway upon the axles with a set of ploughs at each end, is tilted so as to bring the hindmost set into work, and when arrived at the headland the attendant has simply to pull down the other end and start the implement in its next course, and so on alternately moving the engine and return pulley at the headlands until the work is finished. A machine of this sort, attached to a portable locomotive engine, such as is used for threshing, will, in my opinion, meet all the requirements of steam tillage, taking into account future improvements which are sure to follow; and, I believe, it would prove a much more economical process for the cultivation of the soil than the system at present in use.

Some three or four years ago I was in communication with Mr. Hoskyns on the subject of steam tillage, and in order to carry out that gentleman's views I sent him a rough sketch of a machine on the principle of rotation, with cutters fixed on a revolving axis, placed behind the carriage of an engine, and of such a form as would enable them to slice the soil, and by a spiral blade lay it in sections prepared for the harrows, or any other process of pulverisation. Not having heard from Mr. Hoskyns, I am not aware of what has been done in this direction, but I am of opinion that an effective machine of this kind might be applied with success on lands which are level, or where the gradients are not steep. The difficulties although not insurmountable are considerable, as the weight of the engine and cutting apparatus is a great drawback to this description of machine.

In the present state of our knowledge it is probably difficult to determine the best principle on which steam

cultivation should be carried out. I am, however, decidedly of opinion that a sum not exceeding 10,000*l.* would be well spent by a commission of two or three gentlemen of undoubted ability who would undertake the duty of investigating the subject, and instituting a series of experiments calculated to ensure unmistakable results as to the best means of overcoming the difficulties, and of establishing a system of operations calculated to meet all the requirements of a new, more perfect, and more economical system of tillage.

Ten thousand pounds is a large sum to be expended for such a purpose, but the agriculturists could not possibly make a better investment; and if this sum were raised by subscription, with a small grant from the Government, the Royal Agricultural and the Highland Societies, I am satisfied the time would not be far distant when the returns would be upwards of 30 to 50 per cent. I would myself, with one or two others, gladly take charge of the inquiry, and by careful experiment and research endeavour to lay a basis for effecting the operations of the farm by steam power at a rate of only one-third the present cost.

REAPING MACHINES.*

Machines of this kind are of great antiquity; they were known to the Romans, and a graphic description is given of them and their uses by Pliny. Those of modern date have many properties which bear more or less directly upon those of antiquity, but we hear nothing of them during the dark or middle ages, and from these remote times up

* The subject of reaping machines was carefully investigated in my report addressed to Lord Stanley of Alderley, President of the Board of Trade, and as that report contains the results of a series of experiments made upon different machines at the Paris Exhibition, I have concluded that I could not do better than submit it for your consideration.

to the present we have few traces of improvement, or successful attempts to substitute machine reaping for the sickle. Various machines were invented in the early part of the present century, though probably the first successful attempt was made by Mr. Smith, of Deanston, in 1812. This machine was followed by those of Ogle in 1822, Mann in 1832, and Bell, of Carmyllie, Forfar, in 1826. Mr. Bell has used his machine and gathered in his harvests by it for the last thirty years, and it is not too much to say that most of those now in use, both in this country and in America, are based upon the principle which he introduced. There is a great similarity in all these machines, and those shown at the Universal Exhibition of Paris exhibited nearly the same characteristics in principle and construction as those at the Exhibition of 1851.

M'Cormick, Croskill, and others, introduced some slight improvements, but the principle of the machine remains unaltered, excepting the receiving boards, which in those brought forward for competition at the Paris Exhibition are exceedingly variable in form and construction, and some of them very ingenious. The period of the Universal Exhibition was most favourable for giving a fair trial to machines of this description, and the month of August afforded an excellent opportunity for testing their merits by direct experiment. Through the liberality of M. Dailly, a distinguished agriculturist and member of the jury, a field of oats on his farm at La Trappe was set apart for the exclusive purpose of ascertaining the properties and proving the value of these machines. On the 2nd of August, 1855, at 11 o'clock, the machines were divided into three groups, and the contest for superiority commenced as follows:—

		Metres.
1st Group	Mr. Cournier's allotment	1628
	Mr. Wright's "	1733
	Mr. Laurent's "	1825
2nd Group	Mr. Mazier's "	1826
	Mr. Manny's "	1900
	Mr. Croskill's "	1958
3rd Group	Mr. M'Cormick's "	1987
	Mr. Dray's "	2250
	The Canadian "	1650

The points to be ascertained, in order to judge of the merits of the machines, were, as far as I could learn, the time required to cut the allotment, the number of hands employed, and the perfection with which the work was executed without injury to the grain. The first group commenced operations by beat of drum at 11 o'clock, all three machines starting at the same time.

Group 1. *Cournier's machine* (*French*), *on Bell's principle.*—This machine (with one horse) cuts clean, but the cutters are liable to be entangled with straw, and a great deal of time was lost from this cause. This defect appears to be common to all the machines when the speed happens to be reduced under two and a half miles per hour. In this respect I found the maximum velocity of the machines to be as nearly as possible three miles an hour, and the knives for every 18 feet in distance, that is, for one revolution of the wheel, made 11 single or 22 double cuts. This machine had a sliding rake motion, to enable the reaper to clear the receiving board of the grain as it was cut. It might be improved and rendered more effective, and would work much better with two horses and a wider cutting board, so as to take a greater width of grain and maintain the speed necessary to a maximum velocity and a maximum result. From the frequent clogging of the cutters it required 67 minutes to cut 1628 square metres of corn. In this machine

the reel for gathering the corn went too fast, and injured its working by striking the grain too high up the stalk.

J. S. Wright's Automaton machine (*American*) executed 1733 square metres in 24 minutes. This machine is nearly self-acting, requiring only a driver and one attendant to follow the machine, in case anything should go wrong. Its novelty consists in a rake worked from the wheel that drives the cutter shaft; it is attached by an arm or connecting rod to the bevel wheel, and by a combination of levers receives a rotatory motion which, along with that in a longitudinal direction, drags the grain forward over the edge of the board; in order, however, to make sure of the discharge, another rake or cleaner strips the before-mentioned one of its load, and lays the straw in parallel lines, ready to be bound into sheaves. This machine, like Cournier's, has some clever devices, but requires further alteration to simplify and make it more effective and complete.

Laurent's French machine.—This machine, like Cournier's, was constantly choking with the straw around the cutters. It is a copy of Bell's, and requires two men at the pole, a driver, and a reaper, to work it. It is a heavy machine, and almost too much for two horses to work. The falling off in the speed was the reason of its entanglement. In all these machines speed is an element of success, as whenever the velocity of the knives and the speed of the machines was reduced, choking and entanglement of the straw resulted. Under these circumstances, it is therefore a consideration of much importance to have these machines of such dimensions as to enable the horses to work them with ease at the required velocity.

Group 2. Mazier's machine (*French*).—This machine is of light construction, adapted for one horse, and cuts a breadth of 2 feet 7 inches in a line all round the field. It

cuts either right or left, by means of the frame containing the cutters turning on a central axis. The knives are worked by a wheel and worm, and are well calculated to cut light grain, such as oats and barley, but might prove inoperative on a field of heavy wheat. The machine, as a whole, was rather slender for the work it had to perform, but if well constructed, and the parts judiciously proportioned for two horses, there is no reason why it should not reap any description of grain. In the attempt to cut the allotment it unfortunately broke down, some of the parts giving way.

J. H. Manny (*United States*).—Mr. Manny's allotment consisted of 1900 square metres, which was cut in 26 minutes. The machine is worked by two horses, and cuts a breadth of 4 feet 6 inches. Mr. Manny speaks highly of his machine, and gives numerous testimonials of its efficiency, exclusive of medals, premiums, and awards from different districts in America, and from various countries in Europe, for its performance. According to Mr. Manny's account, "it will cut *either grass or corn when down, wet or dry,* and in whatever direction the wind blows, without being stopped for a single instant." He further observes "that it can in a few seconds be converted from a reaper into a mower, as the only thing required is to withdraw the platform and change the knife of the reaper into the cutting scythe of the mower."

"The cutting apparatus for corn or grass is made in such a way that it cuts as well backwards as forwards. When the machine is reaping the wheat is received on the platform, gathered, and put into a heap by the action of a wind board, and by a single stroke of his rake the attendant puts the grain down on the ground, at the back of the machine, in the shape of already made sheaves, which only require tying."

It will not be necessary to follow Mr. Manny in his description, which evinces great confidence in the superior performance of his machine; suffice it to observe, that it did its work moderately well, though some parts were not clean cut.

Croskill's machine (*English*) is an improvement upon Bell's, and in great repute among the farmers of the North Riding of Yorkshire and other parts of England. In the hands of Croskill it has received several improvements, but unfortunately on this occasion the key of the connecting rod that works the knives got loose, dropped out, and stopped the process of reaping; under these circumstances it was considered advisable to withdraw the machine, and leave the field open to other competitors.

Group 3. *M'Cormick's machine* (*American*).—This reaper is probably one of the best machines of its class. It reaped 1987 square metres in 17 minutes, and judging, not only from the quantity of work done in so short a time, but from the manner in which the ground was cleared and the grain cut, it evidenced much greater perfection in its operations than any of the others whose powers were brought to the test.

It cuts a clean track of 5 feet 6 inches wide, and performs the operation with a degree of certainty and precision sufficient to account for the very short time in which the allotment was cut. This machine, however, like most others, is susceptible of still further improvements, and I am glad to find that Messrs. Burgess and Key, the makers, are about to introduce a new movable apparatus, consisting of Archimedean screws, for delivering the grain from off the receiving board as it is cut. This would render the machine much more perfect, as its great defect was the way in which the grain was delivered from the platform, and the evident want of some method of laying the heads

and straw parallel, and in bundles or sheaves, and so as to clear the track for the horses on the return cut.

Wm. M. Dray and Co.'s machine (*English*) is of an exceedingly compact form. It is entirely without a reel for gathering in the corn to the cutters, and requires only one man as a reaper to watch the cutters and discharge the corn as it is received upon the board or wooden platform behind. The cutters are five feet wide, and it reaped 2250 square metres in 35 minutes. The peculiar features of this machine are its portable construction, and the receiving board which moves upon an axis, and is tilted by the pressure of the reaper's foot, so that the grain drops behind ready for the person who follows to bind and tie it up.

The only objection to this process is that it requires the binding to be done immediately, otherwise the working of the machine would be impeded, and the horses at every succeeding cut would have to trample over that previously reaped. This appears to be the chief defect in the machine; a different clearing apparatus to effect the discharge of the cut grain in a lateral direction would render it much more valuable. It would give time for binding up the grain into sheaves, and at the same time it would clear the track for the horses and machine in their return for the next cut.

The last machine (Canadian) was withdrawn from some cause not explained.

The following Table, which Mr. Edward Coombes got up at my request, exhibits the results of the different trials.

Trial of Reaping Machines on the farm of Mr. Dailly, at La Trappe, near Paris, 2nd August 1855.

No.	Maker's name.	Country.	Breadth of cutting part.	No. of square metres cut.	Time.	No. of Horses.	Price.	Remarks.
			ft. in.				£	
1	Cournier .	France .	4 3	1628	67	1	26	Driving-wheel 3′ 3″; crank makes 11 revolutions to 1 of the wheel; knife not serrated.
2	J. S. Wright	U.S. America	5 3	1733	24	2	36	Diameter of driving-wheel 4′ 4″; crank makes 24 to 1.
3	Laurent .	France .	5 0	1825	66	2	—	Diameter of driving-wheel 3 feet; crank makes 15 to 1 (similar to Bell's).
4	Mazier . .	France .	2 7	Broke down		1	—	Small machine, cutting right or left. Knives worked by wheel and worm.
5	Manny . .	U.S. America	4 6	1900	26	2	26	Diameter of driving-wheel 2′ 6″; crank makes 13 to 1.
6	Croskill .	England	5 0	Broke down		2	45	
7	M'Cormick	U.S. America	5 6	1987	17	2	30	
8	Dray . .	England	5 0	2250	35	2	25	
9	Canadian machine .		6 6	Withdrawn		2	—	

On a careful examination of the machines entered for the prizes, it should be observed that in every one of them an attempt was made to effect a certain purpose by means of transmission calculated to retard rather than to facilitate the process of cutting. It is true that in machines of this kind, where horses are employed as a motive power, it is desirable to make the parts as light as possible, and to effect the motion of cutting, &c. with as light wheels and motions as can be made. But the small wheels and their attachments, as applied to these machines, appear to me to be the very worst and heaviest parts of the machine, and I would earnestly urge upon the makers of reaping machines the absolute necessity of increasing the dimensions of the gearing which works the cutters, and at the same time that the journals and ends of the shafts should be attached to *one casting*, so that they cannot vary in position, but must move,

and, speaking technically, come and go with the machine. These alterations being made, and proper clearing apparatus attached to the receiving-boards, we might then reasonably expect the machines to perform the labours of the harvest with much greater certainty and rapidity than is at present possible.

From the above Table it will be seen that M'Cormick's American machine performed the most work in the least time; that Wright's and Manny's executed as nearly as possible the same quantity of work in the same time, there being a fraction in favour of Manny; and that after these Dray was next in the order of time and quantity of work done.

Reducing the whole work done to a standard of 2000 square metres, the competing machines will stand thus:—

		Metres.		Minutes.	Mean.
M'Cormick's	would cut	2000	in	17·11	25·81.
Manny's	"	2000	"	27·36	
Wright's	"	2000	"	27·69	
Dray's	"	2000	"	31·11	

In the investigation of this subject we have hitherto confined our observations to the machines. There is, however, another element equally important and essential to the efficiency of the process of machine reaping, and that is *the preparation of the land;* and in fact before we can look forward to complete success, the surface of the soil must be levelled and the present injurious system of ridges done away with. To apply machinery to the labours of the farm, the land must be prepared not for *hand* but for *machine* culture, and the successful introduction of reaping machines will chiefly depend upon the preparations that are made for their reception. The system of ridges may be tolerated and overcome with the sickle, but to give to the new process of reaping by machinery its full value, a totally different plan of operations must be pursued, and the fields laid down with a

perfectly smooth surface. The larger description of stones and other obstructions should be removed, and in place of the superfluous waters not required for the nourishment of the plants being allowed to flow between the ridges on the surface of the field, sweeping in heavy showers everything before them, the new system of drainage must be adopted, and the water carried *under* in place of running *over* the surface.

To make a machine, such as a reaping machine work well, everything must not be left to it, the agriculturist must do his duty as well as the engineer; and that duty duly performed *on both sides* will secure certainty of action, solve the great problem of machine labour, and effect satisfactory results. When this is accomplished, and not till then, we may look forward to the crops being well and quickly gathered in by machinery, to the exclusion of a laborious process effected with difficulty and often imperfectly by the human hand. One of the greatest advantages of machine over manual labour is the great saving of time effected by the former, and this alone is of vast importance in countries like England where the climate is variable, and where a whole harvest may be lost or seriously damaged by a wet season, unless rapidly cut and stored. At such times the machine reaper becomes invaluable, and cannot fail, when properly constructed and properly applied, to prove a great national benefit.

LECTURE III.

ON THE RISE OF CIVIL AND MECHANICAL ENGINEERING, AND ITS PROGRESS TO THE PRESENT CENTURY.

It is instructive to learn from history how men lived during remote periods when the great names of antiquity flourished; to note the condition of our own forefathers, and to trace the course of mechanical improvement in its connection with human progress in all its stages. During the dark ages of a nation's history, before it has emerged from the clouds of barbarism, what few mechanical contrivances exist are rude and imperfect, and ill calculated to alleviate the toil of hard manual labour; but when a movement in advance has been made, and civilisation dawns more brightly, it becomes highly interesting to walk side by side with the great men to whom that progress is due, and to follow them through all the troubles and difficulties they had to encounter in the pursuit of knowledge and the introduction of mechanical aids and substitutes for labour in the operations of daily life.

Let us consider the subject for a moment, and briefly examine the condition of the different races to whom we are indebted for many of the blessings we now enjoy, and from whom we have derived mechanical aids that have come down to us from remote periods of the world's history.

CONDITION OF CONSTRUCTIVE ART IN VARIOUS NATIONS DOWN TO THE SEVENTEENTH CENTURY.

Some nations, such as the Chinese and Hindoos, attained a comparatively high state of civilisation for ages antecedent to the conquests of the Greeks and Romans. The plough, the spindle, and the loom have been known to ancient nations from the earliest times. Astronomy, geometry, mathematics, and other branches of science were cultivated by those people to some extent, and many of the useful arts were successfully practised, but that upon a scale better adapted to the supply of their ordinary wants than indicative of a rate of progress calculated to develope to any great extent the inventive faculties of the age in which they lived. Such was the position of the oriental nations more than a thousand years before the Christian era; and looking to the advancement which they might have attained in science and art, it is lamentable to find that their progress was checked by conquest and bad government, and that they have since become a stationary people.

What, then, is the cause of this non-progression, which for thousands of years has locked up the inventive faculties of races to whom we are indebted for the first principles of science and the rudiments of civilisation? Probably we shall not find it to have arisen from any natural deficiency, nor from the want of those higher powers of intellect which constitute genius in every age and country; on the contrary, we may trace the absence of progress and the national decline to a stationary and restrictive principle of government, united with religious dogmas and a decaying faith, which effectually deaden the inventive faculties, and paralyse the energies of an otherwise gifted people.

That these obstacles have existed from the earliest periods is evident, and that they still operate is observable

at the present time in many countries where the government is absolute. The Chinese, for example, are the same people at the present day that they were in the age of Confucius, and they may continue so for many ages to come, unless roused to action by subjection to a foreign power, or some other cause calculated to bring them under the influence of western civilisation. The Mahommedan successors of Timour, and the followers of the prophet, are equally adverse to change; and so long as a prescribed form of government exists, associated with an intolerant creed, we may look in vain for that progress which is so happily attained amongst the more cultivated intellects of the west.

The Orientals have long ceased to exercise any influence upon the development of civilisation in other countries. It is evident, however, that Egypt attained at an early period a high degree of refinement, and gave a marked impetus to the arts in all surrounding countries. It is evident, from the quantities of linen which have been discovered shrouding the remains of their rich or distinguished men, that spinning and weaving were largely practised by the Egyptians, and judging from the splendid remains of their temples, pyramids, and public buildings, we may reasonably infer that practical science and useful art were largely cultivated, and applied in the construction and erection of these vast memorials of antiquity, which have stood the test of time for ages almost unimpaired. In the irrigation and tillage of the soil the Egyptians must have attained considerable perfection, and the quantity of wheat grown and exported indicates the industry of the Egyptian people and the great fertility of the soil.

From the Egyptians we descend to a people who, of all others, ancient or modern, have excelled in the refinements of architecture and sculpture. To the Greeks we owe the application of the true principles of harmony in

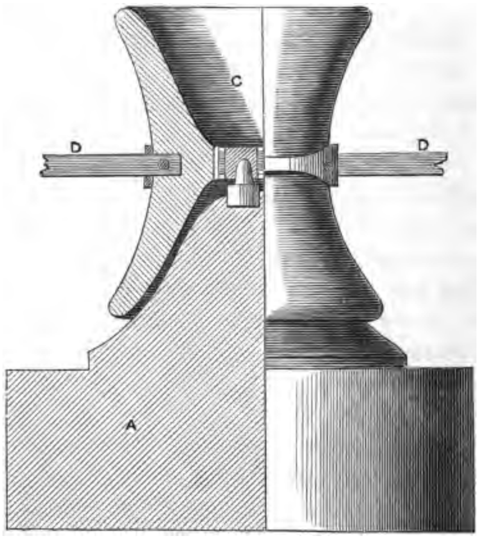
these arts, and the development of beauty of design and symmetry of proportion. That illustrious people were no copyists of the art of surrounding nations, but were perfectly original, and struck out for themselves new conceptions in design and construction. They made the profound and loving study of nature the high road to perfection, and rendered symmetry in the development of natural forms the grand criterion by which the artist was judged. These were the characteristics of ancient Greece, and with all our boasted powers of invention we have never been able, up to the present time, to originate anything comparable in beauty to the five orders of architecture as they came from the hands of the Greeks.

How unfortunate has it been for art and for the world that the constant wars and contentions amongst the Greek states, against the Macedonian and other powers, should have retarded the progress of the useful arts, and ultimately sapped the liberties of the Grecian people, destroyed every hope of further improvement, and left them an easy conquest to the rising and more powerful republic of the Romans.

To the Romans, who shortly after the conquest of Greece became masters of Europe, we are indebted for many works of art and mechanical adaptation. It is supposed that water, as a motive power, and wheels with buckets and floats, were applied by them in grinding corn and pumping water. Of their corn-mills, some were on the principle of the pestle and mortar, and others consisted, like our own, of revolving stones. Some of these latter mills are yet to be seen in the baker's house which has been uncovered at Pompeii, where I had the opportunity of sketching one about a year since. Fig. 28 will explain the principle of these interesting remains. A is a block of rough leucitic lava, cut into a conical form, with an iron pivot at the top, which supports the movable stone B, composed of the same material, and hollowed out to em-

brace the conical fixed stone A. The upper part was similarly hollowed to form the hopper C, from which the corn, passing by degrees down between the abrading surfaces of A and B, as the mill was worked, was crushed to powder. It is not certain in what way motion was imparted to the running stone, but I am inclined to think from the number of stones of this kind, placed in close proximity, that the grinding process was effected by a see-saw motion, produced by slaves working at the extended

Fig. 28.



poles D D, which are fixed in the sockets in the upper stone. The bran was probably separated from the flour by means of a sieve; and it may be remarked that in the same building with the mills, at Pompeii, the ovens may still be seen, built of brick, almost in every respect similar in form to those in use in this country.

There can be no doubt as to the fact that the Romans prac-

tised the arts of spinning and weaving, but, generally speaking, they were rather the patrons than the cultivators of art; and whether we view them as agriculturists, architects, or mechanics, we shall find that the great works in Rome, and in the Roman towns of Italy, were designed and executed by foreigners, and chiefly by the Greeks and Tuscans. The Romans laid the whole of their vast conquered possessions under contribution for the gratification of their own ambition and the enrichment of their own homes and cities. The results of their conquests are still to be seen in the magnificent remains of monuments and edifices, and works of public utility scattered throughout Italy and the provinces. The scenes of rapine and murder which were enacted during the latter days of the empire, and the consequent insecurity of life and property, with the increasing luxury and indolence of the people, readily account for the stagnation of useful art which preceded the decay of the empire.

The consideration of the state of art amongst the Romans brings us down to the period of Alaric and his successors, when the empire was destroyed by the inroads of the Northern barbarians, and all progress in the arts stayed for almost a thousand years. About the beginning or middle of the fifteenth century, and during the Italian Republics, the light of civilisation began again to dawn upon a new generation of men. In 1474 was born Michael Angelo Buonarotti, one of the greatest painters, sculptors, and architects of any time; one of the ablest designers, and a skilful anatomist. His works are celebrated throughout all Europe, and the beauty of his paintings and the originality of his conceptions in the highest regions of art, are to this day the subjects of universal admiration.

After Michael Angelo came Galileo, born in 1564, and to that great man we owe the telescope and pendulum, applied by his son Vincenzio to the regulation of the clock. He

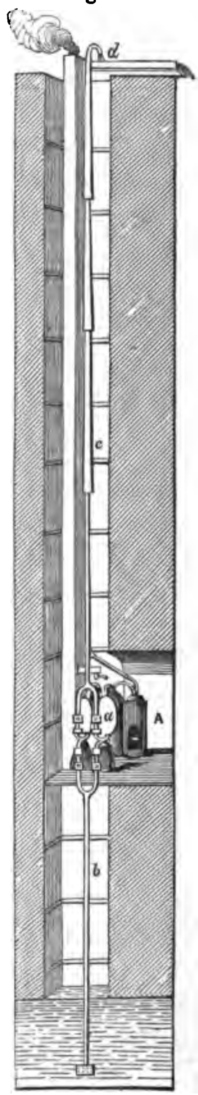
was one of the first of the school of experimental philosophers who, abandoning the barren methods of the schoolmen, have produced such brilliant results in physical science.

Michael Angelo in the fine arts, and Galileo as the representative of theoretical and experimental science, were followed by those who in our own country led the van of progress in another department. The Marquis of Worcester, in his "Century of Inventions," announced the steam engine; and however crude his invention may have been, it must still be taken as the starting point from which have sprung the vast developments of steam power. The Marquis actually erected one of his engines of about 2-horse power on the banks of the Thames, and it was employed in supplying the town with water.

In "The Journal of the Visit to England of Cosmo de Medicis, Grand Duke of Tuscany," in 1699, there is an interesting record of this engine of Worcester's. "His highness," writes his secretary, "went again after dinner to the other side of the city, extending his excursion as far as Vauxhall, beyond the palace of the archbishop of Canterbury, to see an hydraulic machine, invented by my Lord Somerset, Marquis of Worcester. It raises water more than forty geometrical feet, by the power of one man only; and in a very short space of time will draw up four vessels of water, through a tube or channel not more than a span in width, on which account it is considered to be of greater service to the public than the other machine near Somerset House."

This interesting document proves that the plans of the Marquis were practical and capable of advantageous employment. Yet it was reserved for Captain Savery to introduce steam generally as a means of raising water. Savery's engine, of which fig. 29 is a sketch, consisted of two boilers, in which the necessary steam was generated, and two receivers with valves, which were placed at the bottom of the mine shaft, about thirty feet above the

Fig. 29.



water to be drained, as at A. The process of pumping was effected by admitting steam into one of the receivers, as *a*, and then cutting off the connection with the boiler. The steam was suddenly condensed by means of a jet of cold water, which, forming a vacuum, the water to be lifted immediately rushed up the pipe *b*, by atmospheric pressure, to refill the receiver. Steam being then admitted from the boiler to press upon the water in the receiver, and all connection with *b* being cut off by a valve, the water was forced up the pipe *c*, and discharged into the trough *d*. The steam in *a* being then again condensed, the process was repeated, and thus by the alternate action of two receivers a continuous stream was maintained.

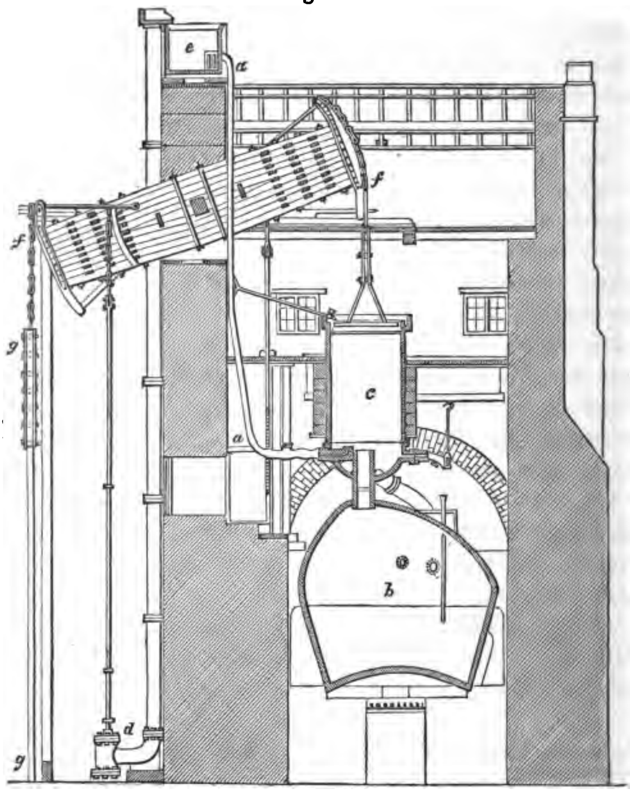
Dr. Papin shortly after this made some contributions to our knowledge of the properties of steam by his experiments with the cylinder and piston, and by the invention of the *digester*, in which he dissolved bones and other animal solids by means of the high temperature which water attains under great pressure. It is upon these researches of Papin that Arago* (in his Éloge of Watt) and other French philosophers, have founded his claim to the

* Arago's Biographies of distinguished Scientific Men, p. 604.

invention of the steam engine. I have taken some pains to inquire into the justice of this assertion and find the claim to be altogether baseless, and to depend entirely upon the construction of a small model which could never have been used for any practical purpose, and cannot be shown to have had any influence on the actual introduction of the steam engine.

Savery's engine, attended as it was by such an enormous

Fig. 30.



waste of steam, was shortly afterwards superseded by that of Newcomen, a far more perfect and economical machine. This engine, introduced in 1705, is well known as the atmospheric engine, having an open-top cylinder, that the atmosphere may press freely upon the upper side of the piston. Fig. 30 represents a large engine on the Newcomen principle, constructed by Smeaton in 1775, at Chasewater; *c* is the cylinder 72 inches in diameter, with its piston of iron coated with wood, it is placed immediately over the boiler *b*, with which it is in communication; *a a* is a pipe for the injection water for condensing the steam, supplied by the pump *d* from the cold water cistern; the reciprocating motion of the piston, *e*, is communicated through the huge timber main working beam *f f*, to the pump rods *g g*, which pass down the mine shaft. In working this engine, the steam was first admitted into the cylinder *c*, and with the weight of the pump rods *g g* immediately dragged the piston to the top of the stroke; a forked rod, worked by the engine, then shut off the communication of the boiler, and opened the cold water injection cock *a*, the result of which was the sudden condensation of the steam in the cylinder, and the formation of a vacuum under the piston; when the pressure of the atmosphere forced down the piston and completed the down stroke, raising at the same time the buckets and plungers of the pumps in the mine, the steam was then readmitted, and the process repeated for every stroke all the day through.* Now it is evident that every time the injec-

* For comparison with other engines, to which reference may be made, we may add the dimensions of this, which was the largest engine Smeaton had seen :—

Cylinder	72 inches diameter.
Stroke	9 feet.

Making from 4 to 9 strokes per minute.

Actual power	150 horses.

Reports of John Smeaton, vol. ii. p. 347.

tion water is admitted the cylinder is cooled, and requires to be heated again at the expense of the steam before another stroke can be effected. This waste of steam with a proportionate expenditure of fuel did not escape the penetration of Watt, and first led him to those modifications which ultimately resulted in the double action engine as at present constructed.

In the earlier engines, the alternate admission of the steam and injection water was effected by hand, by means of cocks, but was afterwards more ingeniously accomplished by the contrivance of the boy Humphrey Potter, who to save himself trouble and gain time to spend with his playfellows, attached strings to the cocks or valves, and caused the main beam of the engine to open and shut them in the ascent and descent of the stroke. Mr. Beighton availed himself of this ingenious contrivance, and made the engine self-acting, by fixing gearing to the valves, worked by plug rods instead of Potter's strings. Potter was, however, the original inventor of self-acting gear, and although we cannot quite approve this breach of duty to which a game of marbles tempted the little fellow, yet we must admit that as a juvenile engineer he was no bad example, when such a man as Beighton adopted his invention, and turned it so successfully to account in rendering the engine thenceforward self-acting.

MILLWORK FROM 1700 TO 1800.

The condition of mechanical art contemporaneously with these inventions, is exhibited in a work entitled *Machines et Inventions approuvées par l'Académie Royale des Sciences,* which records most of the new discoveries in practical science from 1688 to 1734, a period of nearly half a century. Most of these inventions are exceedingly crude and imperfect, but some are ingenious and curious. Amongst

them we find an immense number of schemes for grinding corn, pumping water, sawing wood, propelling vessels, boring cannon, rolling lead, &c. They also contain drawings of the earliest forms of the steam engine.

The use of cast iron and bevil wheels appears not to have become general until the latter part of the last century. The whole of Smeaton's designs for mills from the commencement of his career to 1782 exhibit only the "cog and rung," or wheel and trundle arrangement.

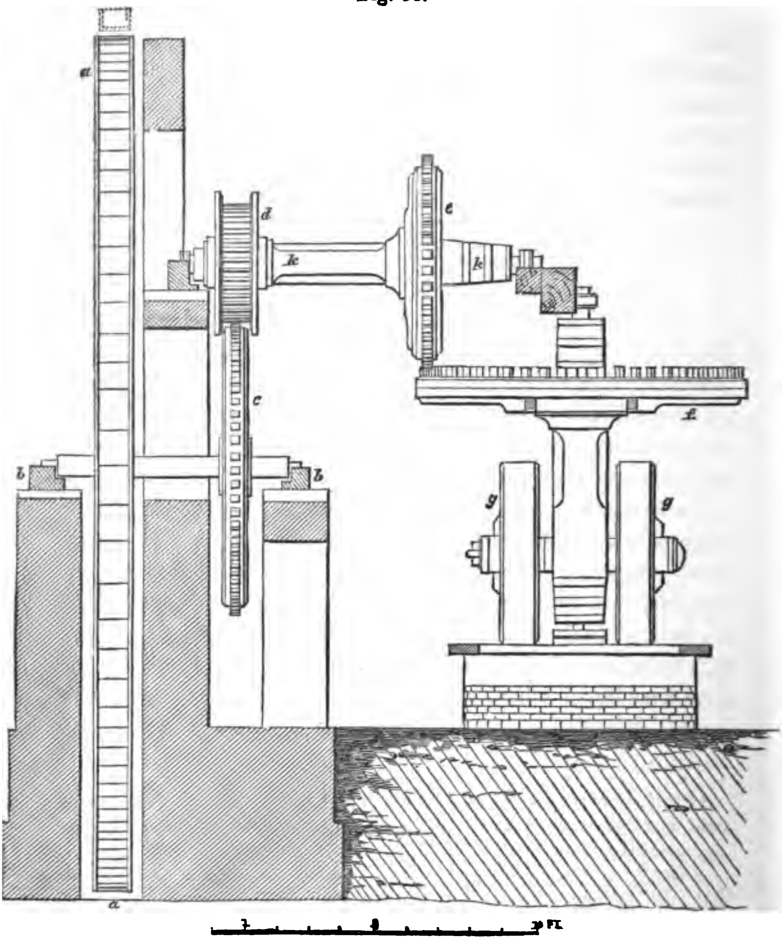
Fig. 31 represents an oil mill, with overshot water-wheel, constructed by Smeaton in 1776, and is a good example of the millwork of the period. The water wheel *a a* is carried upon a solid cast iron axis *b b*, and its movement is transferred by means of the spur-wheel *c*, and trundle or wallower *d*, to the horizontal shaft *k k*, and again by the spur cog-wheels *e*, *f*, to the vertical shaft which carries the heavy oil stones *g g*. It may be observed that the water for this wheel was actually raised by a steam engine, no more direct mode being then known of converting the reciprocating action of the piston and cylinder into the rotatory movement required by machinery.*

In Smeaton's time the shafts were made almost universally of wood hooped with iron, and with gudgeons of the same material, sometimes turned and sometimes not, running in a block of hard wood, or a lump of whinstone, as best suited the convenience of the millwright. Cast iron in millwork began to be introduced about 1770–80. The first bevel wheel seen in Scotland was at a corn mill in Ayrshire about 1770, and the same wheel was retained

* With an engine properly constructed, of twenty-five inches cylinder, I can undertake to raise to the height of thirty feet, 1000 gallons, wine measure, per minute, with the expense of 1 cwt. 3 qrs. coals per hour, and I do apprehend that if a new engine were set about in conjunction with this mill, that such an engine would be made for 350*l.* or thereabouts.—*Smeaton's Reports*, vol. ii. p. 401.

as a relic, forming part of a dial stand in front of the house of Mr. Murdock of Soho. Arkwright is said to have used bevel wheels of iron on a small scale in 1775, and in

Fig. 31.



the Albion Mills, erected in 1783 and 1784, of which the millwork is due to John Rennie, the whole of the wheels and shafts, including the bevel wheels for driving the upright shaft, were of cast iron. The exact period when bevel wheels became general is uncertain, but the wheel and trundle disappeared during the days of Andrew Meikle and his successor John Rennie. At a later period still cast iron for shafting was in turn superseded by wrought iron, a change in the carrying out of which I myself took an active part. I can recollect the ponderous drums and heavy shafts of former days, which used to utter groans and complaints at every revolution. Such a shaft with its wooden drum is shown in fig. 32, as it existed in many of

Fig. 32.

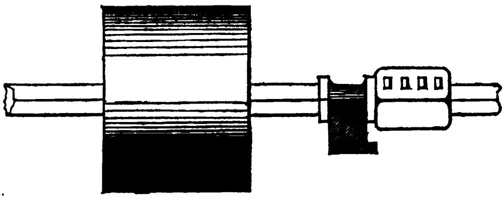


Fig. 33.

our cotton mills only fifty years ago, and fig. 33 exhibits its modern descendant of polished wrought iron, about which I may have more to say in the next lecture.

These remarks bring us to a period in the history of the useful arts from which we may date the commencement of those improvements and discoveries in mechanical science which have effected a change in the condition of men of all countries, and from which we now reap benefits un-

known to the generations of the past. To what extent these discoveries may yet be carried, it is not for me to determine, but looking at the great perfection at which mechanical science has already arrived, he would be a bold man indeed who would venture to set limits to the development of human invention. In directing your attention to the important events that have occurred from time to time during the past and present century, I shall divide the subject into two periods—the first extending from 1750 to 1800; the second from 1800 to the present time.

ENGINEERING DURING THE LATTER HALF OF THE EIGHTEENTH CENTURY.

At the commencement of 1750 the title of engineer was unknown in the vocabulary of science; it was reserved for Brindley and Smeaton to establish a distinct profession under that name. Previously to that time the engineering of the country was chiefly effected by architects. Inigo Jones designed a bridge of three arches in 1636; Labelye built Westminster Bridge, and Mr. R. Mylne, the father of the present engineer of that name, built Blackfriars, which was commenced in 1760 and finished in 1771. From that time to the present nearly the whole of the bridges of this country have been built by engineers.

One of the most successful bridge-builders and engineers of his time was Smeaton, who, at the early age of eighteen, had made himself acquainted with practical mechanics, and devised some ingenious contrivances for measuring a ship's way in the water. In 1753 he was elected a Fellow of the Royal Society, and in 1759 he was honoured with the Society's gold medal for his paper "*On the natural powers of water and wind to turn mills.*" In 1759 he completed the Eddystone Lighthouse, which for a hundred years has resisted the storms of the Atlantic; a work of

great difficulty, that has not been surpassed by any similar construction up to the present time. From 1759 to 1764 he appears to have to some extent retired from active engagements, as we hear little of him till the construction of the bridge at Perth, which was begun in 1765 and finished in 1771. From that time till his death in 1792 he was the leading engineer of the kingdom. He made the river Calder navigable, planned and completed the navigation of the great Forth and Clyde Canal; erected the blowing machinery at the Carron Iron Works; and there was no man of his time who constructed so many mills or introduced into that department of mechanical construction so much talent or so many improvements. Mr. Smeaton never trusted to theory where he had the power and the means of testing his improvements by experiment. His experiments were the basis on which he founded his constructions; he never trusted to chance, and hence his success. We owe him a debt of gratitude for many discoveries and improvements, and may consider him the father of engineering; the model on which his successors Rennie and Telford were moulded.

In the same field of study and industry was Brindley, the constructor of the Bridgewater Canal, one of nature's engineers. No two men could be more dissimilar in taste and character than Smeaton and Brindley; yet both were men who left behind them lasting monuments of their resources, and although they commenced their career under different auspices,—the one as an attorney—the other as a working millwright with no education,—both of them attained eminence in the double capacity of mechanists and civil engineers. Brindley was born at Tunsted, in Derbyshire, in 1716, and laboured hard for a livelihood till seventeen years of age. Having a taste for mechanical pursuits he bound himself to a millwright, and during his apprenticeship obtained the confidence of

his employer, of whom he eventually became the instructor. He then commenced business on his own account, and such were his inventions and contrivances that constant employment was secured him to an extent never realised by any of his predecessors. In this way he laboured successfully till he was forty years of age, and during that period, amongst other works, he erected at Clifton, near Manchester, a water engine for draining a coal mine, a silk mill at Congleton, and various other constructions considered at that time of great importance. At Newcastle-under-Lyne he erected a steam engine, the boiler of which was made of brick, and the cylinder of wood hooped with iron. How this engine worked, we are not informed; but the whole scheme was opposed and ultimately swamped by some interested competitors. The crowning efforts of Brindley's genius, however, were the Great Bridgewater Canal, and the viaduct across the Irwell, at a height of forty feet above the river, by which he effected a communication between Manchester, Worsley and Runcorn. This great work was begun in 1759, and the first boat entered Manchester in 1762. Amongst other similar works executed by Brindley, was the Union or Great Trunk Canal, between the Trent and the Mersey. After this time the country was penetrated in every direction by canals; some constructed by Brindley, Jessop, and Smeaton, and others of later date by Rennie and Telford.

In the construction of canals, millwork, and water engines for raising coal from the mines (some of which are still in existence between Worsley and Bolton), Brindley was without an equal; and the country is indebted to his genius for penetrating mountains by tunnels, and for conveying navigable waterways over rivers by those aqueducts which give to the canal system the novel feature of a river suspended upon arches high in the air, with vessels floating upon it, above others on the river below. By the

fertile resources and indomitable perseverance of this distinguished and self-taught engineer, all these objects were attained in the face of difficulties sufficient to discourage the ablest and best educated men of the age in which he lived.

And I would here remark for the benefit of the young men now before me, that this brief and imperfect review of the career of our two first engineers ought to teach us that the only road to fame and distinction in our respective professions is through the portals of persevering industry. In that arena we must labour, and in that field expand our intellects and mature our understandings, not by looking on, but as hard workers in the pursuit of knowledge and in the exercise of our callings. It is immaterial what profession or business you pursue; to succeed in it you must work, and to become a leader you must throw the whole of your powers, physical and mental, into the contest, otherwise you are sure to lose and to be distanced in the race. To become a great man you must be a hard worker, and I can tell you from experience that there is no labour so sweet, none so consolatory, as that which is founded upon an honest, straightforward, and honourable ambition. Take for your examples the two great men I have brought under your notice, and let their actions stimulate you to exertion in the paths of honest and persevering industry.

THE STEAM ENGINE, AND THE RESULTS OF ITS EMPLOYMENT SINCE THE TIME OF WATT.

I must, however, observe that Brindley and Smeaton are not the only men to whom the country and the world are indebted for the commencement of a new era in mechanical progress. Other labourers were in the field,

of a character equal, if not superior, in inventive talent to either of them. To Watt and Arkwright we owe a debt of gratitude which we shall never sufficiently repay. We may write their histories, or raise monuments to their memories, but these are of little moment when compared with the splendid results which have flowed from their discoveries, and influenced the relative positions of the whole human race. If we compare the steam-engine as it left the hands of Watt, with its puny condition and restricted applicability when he first became acquainted with it, we are lost in amazement at the extent of its power, the beauty of its construction, the docility with which it adapts itself to all circumstances; and all these qualities are due to him and to him alone.

At the present time there exists in the British empire a total steam power equivalent to that of more than 8,000,000 horses, working ten hours a day; or if we add to this the engines afloat we have a total of 11,000,000 of horse-power, a force vastly exceeding that of all the living horses in the kingdom. Compare the state of our manufactures, the extent of our commerce, the facilities of transport which we now enjoy, with the same in the early days of Watt, and tell me whether this amazing increase, this immense development of our resources, is not owing to his genius?

It is impossible to form a just conception of the benefits that have arisen from the introduction of the steam engine. It is applicable to every condition in life, and has multiplied the material comforts of mankind to an extent without a parallel in the history of nations. It has given a subsistence to millions who but for it would never have existed, and it has given employment to thousands of an intellectual character which no other means could have furnished to the same extent. Now in every country where coal, wood, and water are found, industry may flourish, and the steam engine be in constant de-

mand. If time permitted, I would cheerfully venture upon a description of the improvements which have been effected in this important machine since the days of Watt, but I have trespassed too long upon your patience, and must curtail my observations within the narrowest limits.

Notwithstanding the variety of forms into which it has been moulded, the steam engine is still the same machine in all its simplicity of principle as when it came from the hand of Watt; it has the same reciprocating action, the same principles of separate condensation, and the same mechanical organisation as it had seventy years ago. What can exceed in beauty of contrivance the parallel motion, the governor, and other motions by which this wonderful machine is rendered effective. Innumerable attempts have been made at its improvement, and yet with the exception of working high pressure steam expansively, and by this means economising fuel, there has been no change in the principle of the steam engine, either in its condensing or non-condensing form. It is still the engine of Watt; his name is stamped as indelibly upon it as Newton's upon the law of gravitation.

In former days many persons looked upon the invention of the steam engine as a social misfortune. If we would credit these imbecile philosophers, the introduction of every machine is an injury rather than a benefit, and the wonderful combinations which we are accustomed to admire for the regularity and harmony of their movements are instruments of mischief, and ought to be proscribed. There can be no greater fallacy than this; the working of our mines, the extension of manufactures, and the immense increase of industrial pursuits, fully testify to the immense advantages which mankind have derived from mechanical contrivances. In this country alone they have given employment and social comfort to millions of the labouring poor, and they have raised the country to a degree of wealth, influence,

and power, greater than she ever before attained in her most promising days of prosperity.

If I had the means at my disposal I would lay before you correct statistics of the steam power which has thus raised our resources in the different departments of mining, manufactures, and transport. Sufficient data are not, however, accessible; but I have estimated the total in round numbers at 11,000,000 horses, working ten hours per day. That is—

Employed in	Nominal Horse Power.
Mining and the manufacture of metal . . .	450,000
Manufactures	1,350,000
Steam navigation	850,000
Locomotion	1,000,000
Total	3,650,000

And as these engines are worked at an average of three times their nominal power, the above numbers represent a force equivalent to *eleven millions of horses;* and taking one person to every nominal horse-power, we shall then have nearly four millions of people to whom the steam engine is giving employment in Great Britain and on board our ships. It is no wonder, therefore, that we revere the memory of Watt, when we look upon the benefits he has conferred upon the world and upon his country.

THE COTTON TRADE.—To Richard Arkwright, an ingenious barber, belongs almost exclusively the merit of those inventions which gave an important impetus to the development of an entirely new branch of industry. The carding, drawing, and spinning of cotton, which eighty or ninety years ago was performed by hand, being spun upon a single spindle, is now increased a million fold, and the value of the cotton manufacture has increased from 2,000,000*l.* to upwards of 60,000,000*l.* per annum, being in the ratio of 30 to 1. Upwards of

1,500,000 bales of cotton were imported into Liverpool in 1857, and the improvements which have followed Arkwright's original inventions have raised the country, with the aid of the steam engine, to her present high state of prosperity.

The late Mr. Kennedy states that the first improvement consisted in the division of carding and spinning into two distinct operations, and progress was first made in the carding, by means of which one boy or girl could work two pairs of stock cards. This continued for a short time, when further improvements followed, until one person could work four or five pairs by holding hand cards against stock cards fixed on a cylinder revolving on its axis, or what is now called a carding machine, the inventor of which is unknown. Next in order came the invention of Hargreaves in 1767, namely, the spinning jenny, by means of which a young person could work from ten to twenty spindles at once. After Hargreaves came Arkwright, whose first mill was built at Cromford in this county (Derbyshire) in 1771, and in 1780 appeared a valuable machine called "Hall-i'-th'-wood," but now "Crompton's Mule," from its uniting the qualities of Hargreaves' and Arkwright's frames.

In the department of weaving we are indebted to Mr. John Kay of Bury for the flying shuttle, which he introduced about the year 1750. This was followed by the improvements of Dr. Cartwright, Mr. Thomas Johnson, Horrocks, and others, who adapted the loom to be worked by power. This was practised on a small scale, but did not come into general use till 1824-5.

THE IRON TRADE of this country is one of the most important, and well entitled to consideration in tracing our national progress. It would be interesting, if time permitted, to notice the gradual advances which have been made during successive ages in the methods of reducing

the ores. The bloomery or open hearth was probably at first employed, the crude product being made malleable under the hammer. This simple process has been in use for thousands of years, and is still practised in Africa, Asia, and even in Spain, wherever the rich specular ores are found. At what period the bloomery gave place to the blast furnace it is impossible to determine: but we find that the process of smelting by the latter had arrived at considerable perfection in the seventeenth century, and castings made antecedent to that date are still preserved: at that time and up to 1740, charcoal was the only fuel employed in smelting, and the consumption of wood for this purpose so threatened the destruction of the forests that prohibitions were issued, and the production of the furnaces reduced from 180,000 to 17,350 tons per annum. The introduction of pit coal for smelting, however, changed entirely the aspects of the iron trade, and from that time it has steadily progressed to its present enormous rate of production.

In 1783-4 Mr. Cort, of Gosport, introduced the now universal processes of puddling and rolling in the manufacture of wrought from cast-iron. When mentioning his name I cannot refrain from adverting to the gross neglect to which some of the greatest benefactors of mankind seem to be doomed, as their only reward for discoveries which have raised their country to a degree of opulence hitherto unknown in the annals of history. Cort, the pioneer of the iron trade, is one of the latest and most flagrant examples of this want of sympathy on the part of a highly favoured nation.

The following returns illustrate better than any comments the steady increase of the iron trade: —

		Tons.
Total quantity smelted in	1740	17,350
" " " "	1788	68,300
" " " "	1796	124,879
" " " "	1820	400,000
" " " "	1827	690,000
" " " "	1854	3,069,874

At the present time the annual produce cannot be less than 3,200,000 tons.

Such has been the advance of one of the most important branches of industry, the support of almost all other trades, and one which united to coal has afforded this country treasures more valuable than a thousand Californias.

In closing this part of my subject, I must not omit to notice Mr. Neilson's application of the hot-blast and the facilities which it has afforded for the reduction of the ores and the greatly increased production of the furnace. Our iron trade has permanently taken a position which, above all other countries, is distinguished for the skill, economy, and magnitude with which its operations are carried on; and we have reason to be grateful to an All-wise Providence, for having entombed in the bosom of our little island such immense and inexhaustible treasures, for the use of its inhabitants and the glory of its name in every part of the globe. Without the advantages of coal and iron, which we possess in such abundance, this country would never have become the cradle of inventive genius nor the workshop of the world.

Another benefactor to his country was found in Josiah Wedgewood, the founder of the porcelain or Staffordshire ware manufacture, so well known for its cheapness and beauty in every part of the globe. To the son of a poor potter at Burslem we are indebted for an entirely new branch of industry, and the many benefits we have derived in our domestic homes from the use of Wedgewood's pottery can only be appreciated by recollections which

carry us back to the days of pewter plates and trenchers. Before Wedgewood's time the earthenware produced in this country was of the coarsest and meanest description, and the quantity produced, even bad as it was, totally unequal to the demand. In this state of the manufacture we were dependent upon Holland and other countries for our supply, until the genius of Wedgewood effected a complete change in the character of the trade, and thus induced not only an ample supply for home consumption, but a large and growing export into the bargain.

It might be interesting to trace the early career, and enumerate the troubles and difficulties he had to encounter in his experiments on earths containing silica: his process of calcination, and his process of vitrifaction in producing a transparent glass, effected a complete revolution in the manufacture, and ultimately produced those splendid specimens of stone and earthenware which, through his skill, industry, and that of the late Mr. Minton, have raised the manufacture of English porcelain to its present high state of perfection.

Other branches of manufacturing industry have advanced at a similar rate, and I might instance the improvements which have taken place in the machinery for spinning and weaving our woollen, silk, and linen fabrics, many of which had their origin in the latter part of the last century; and the real source of which is to be found in the various inventions employed in the manufacture of cotton; to these improvements, however, I cannot now advert, and I must leave for another evening the consideration of the further development of these branches of industry which have left their impress upon the face of the country and on the character of the present generation of men.

LECTURE IV.

ON THE PROGRESS OF CIVIL AND MECHANICAL ENGINEERING DURING THE PRESENT CENTURY.

In taking up again the subject of the progress of Civil and Mechanical Engineering, I must be permitted to explain that a number of the distinguished men who contributed to its advancement in the eighteenth century, continued at the head of their profession during the first twenty to thirty years of the nineteenth. Rennie, Telford and Watt were still living when Bramah, Brunel, Maudslay and Donkin rose to a high position in their respective professions. For nearly forty years between 1790 and 1830, this phalanx of engineering talent had the field to themselves, and scarcely any work of importance was accomplished without one or other of them having been consulted.

I well remember that in the early part of my own career, when I first entered London, forty-seven years ago, a young man from the country had no chance whatever of success, in consequence of the trade guilds and unions. For myself, I had no difficulty in finding employment, as it was granted me at once by Mr. Rennie: but before I could commence work, I had to run the gauntlet of the trade societies; and after dancing attendance for nearly six weeks, with very little money in my pocket, and having to "box-Harry" all the time, I was ultimately declared illegitimate, and sent adrift to seek my

fortune elsewhere. There were then three millwright societies in London — one called the old society, another the new society, and a third the independent society. These societies were not founded for the protection of the trade, but for the maintenance of high wages, and for the exclusion of all those who could not assert their claims to work in London and other corporate towns. Laws of a most arbitrary character were enforced, and they were governed by cliques of self-appointed officers, who never failed to take care of their own interests. It is true that in those days mechanical science was at a comparatively low ebb. Millwrights and mining engineers were in those days the only men calculated to execute a sound piece of mechanical work; there were no mechanical engineers, and most of the steam-engines, pumps, mills, and other similar constructions were executed by that class; and it is only doing them justice to say, that throughout the whole of the three kingdoms, they were the only men on whom the country could rely for the efficient discharge of these important duties.

In those days a good millwright was a man of large resources; he was generally well educated, and could draw out his own designs and work at the lathe; he had a knowledge of mill machinery, pumps, and cranes, and could turn his hand to the bench or the forge with equal adroitness and facility. If hard pressed, as was frequently the case in country places far from towns, he could devise for himself expedients which enabled him to meet special requirements, and to complete his work without assistance. This was the class of men with whom I associated in early life — proud of their calling, fertile in resources, and aware of their value in a country where the industrial arts were rapidly developing. It was then that the millwright in his character of "jack-of-all-trades" was in his element; all the great works of the country connected with

practical mechanics were entrusted to his skill; and notwithstanding the intemperate habits of the period which too frequently trenched upon his time and his health, he seldom failed in the duties he had to perform. It was no wonder, therefore, that at the commencement of the new movements in practical science, occasioned by the inventions of Watt and Arkwright, the millwright should assume a position of importance. Under these circumstances, to use the expression of the shops, the men were masters, all having the same wages — seven shillings a day and their drink, and it was then, or some time before, that the societies of which I have spoken were formed, and continued for years to exercise an unlimited sway over the talent and industry of the metropolis and other corporate towns. I am sorry to say that the same intolerant and exclusive system is still in operation in particular trades, and it is much to be regretted that intelligent workmen cannot perceive its destructive influence on the comfort and prosperity of themselves and their families. It is in vain to point out the dangers arising from the conversion of benefit societies into trades' unions with paid secretaries, treasurers, &c. And the designs which these functionaries have upon the subscriptions are forgotten or neglected until the whole of the accumulated capital is involved in fruitless contests, and the men are left, without money and without employment, to bewail their imprudence in a state of helpless destitution. A few years ago there was a striking illustration of its injurious influence in the case of the "Amalgamated Engineers," and according to the *Times* of December last (1858), things are not much better in some cases at the present time. "The Letter Press Printers' Union affixes a stigma to all operatives who choose to take care of themselves, and venture to manage their own concerns. A printer not belonging to the Union is called a 'rat,' and Union men

positively refuse to work in his company." This is no new case, as I have found from experience both as a journeyman and as a master; and I leave it to the good sense of this meeting to decide whether it is just, whether it is for the benefit of either the operatives or the public, that the energies of individuals should be thus crippled, and the exercise of their profession denied them from the illegal exercise of control by men who create, for their own selfish ends, only misery and discontent in the families whose interests they profess to represent. I mention these cases to show the injurious working of a system of protection and uniform pay, and the jealousy and exclusiveness of the trade guilds in maintaining the institutions of the fine old times of good Queen Bess*, when you had to be a seven years' apprentice or the eldest son of a journeyman or freeman of the city to which you belonged, before you were permitted to work. Such restrictions as these threw a blight over the bright opening days of a new era, and retarded our mechanical progress as much, if not more, than the expensive and sanguinary war in which we were at that time engaged. At the Peace of 1815 many of these evils were removed, and in giving to the nation rest it gave time for inquiry into abuses, which led more or less to the extinction of the exclusive system, and left open to all classes *a fair field and no favour* in the race of national progress.

Probably no class has derived greater benefit from these changes than that to which I belong; it has now full scope, and I have to congratulate you that we live in an age and country in which every facility is afforded for improvement, and where the inventive faculties are appreciated and fostered in every department of science and art.

* It was considered in those days that an apprentice could not learn his trade or handicraft in less time than seven years, and hence the privileges granted to corporate towns.

About the year 1785, John Rennie (who served his apprenticeship as a millwright with Mr. Andrew Meikle, of Phantassia, near Edinburgh, the inventor of the thrashing machine,) was employed by Boulton and Watt, in the erection of the Albion Mills; and in the construction of the mill work and machinery of that establishment the proprietors received most able assistance from him. I believe he was the first to introduce cast-iron in improved forms and for purposes for which wood alone had previously been employed, and displayed considerable skill in the adaptation of metal to such purposes. His water-wheels, mills, &c., were considered models of perfection, and the arrangement of the cistern, shuttle, &c., of the former was so nicely adjusted as to save every drop of water and turn it to account. The construction of this machinery led Mr. Rennie to the study of hydraulics and hydrodynamics, in which, from his native resources, he soon became celebrated as the worthy successor of Smeaton. As a millwright Mr. Rennie was one of the most successful in the profession, and his works yet remain in the flour-mills at Wandsworth, the rolling and triturating mills of the mint; and many others bear testimony to the accuracy and skill of the constructor. As an architect and engineer also, Mr. Rennie stands quite pre-eminent; and it is almost impossible to enumerate the great works which emanated from his hands. As a bold and ingenious engineering work, we may mention Southwark Bridge, of three arches of cast-iron, which for solidity and span has not an equal even at the present time. For architectural beauty and harmony of curvature, no structure surpasses Waterloo Bridge; and if to these we add the bridges of Kelso, Musselborough, Boston, New Galloway, and others, we shall find that as a bridge builder Mr. Rennie was without a rival, with the exception only of Telford, during the whole of his useful career. Rennie, moreover, was largely

engaged in the construction of canals and harbours, and his opinion and assistance were sought for from all quarters. During the greater part of his career a rage for canals prevailed, not dissimilar to that at a later period for railways. The Lancaster, Rochdale, Portsmouth, Birmingham, Grant Western and Crinan canals; the Plymouth breakwater, and the docks at Hull, Greenock, Leith, Liverpool, Portsmouth, Chatham, and Sheerness, bear witness to Rennie's skill as a civil engineer; and so multifarious were his resources, so persevering his industry and sound his judgment, that no one will be disposed to deny that he worthily earned a niche in the temple of fame. It is recorded of him that his conversation was always instructive and amusing; he possessed a rich fund of anecdote, and like his old friend, James Watt, would tell a Scotch story with a relish and humour highly characteristic.

Next to Rennie, and equally renowned as a civil engineer, was Telford, the son of a shepherd, born in 1757, in the pastoral district of Dumfries and Roxburgh, and brought up to the trade of a stone-mason. He received the rudiments of his education in the parish school of the village of Westerkirk during the winter time, and in summer he assisted his uncle as a shepherd. Whilst thus occupied he procured some books from his village friends, and by these means employed his time to good purpose. In early life he was a poet, and during the time he was a stone-mason, and even for some time after he left Scotland, he cultivated the muses and published at Shrewsbury a poem, entitled "Eskdale," descriptive of the scenes of his early life:—

"Here lofty hills in varied prospect rise,
Whose airy summits mingle with the skies,
Round whose green brows and by the aged thorn,
The early shepherd seeks his flock at morn;

> Or on the sunny side, at noontide laid,
> Sees his white charge in gay profusion spread,
> While round the knowe, beneath the inspiring sun,
> His bounding lambs their playful races run."

He also wrote and published an address to Robert Burns in the Scottish dialect; but these flights of the imagination ultimately gave way to the more engrossing duties of a profession, upon the success of which his fame now rests.

Telford, though an older man than Rennie by four years, did not come into notice as an engineer until the latter had attained to considerable distinction. Towards 1792-3, we find him practising as an architect and surveyor in the county of Salop, and there he commenced his career as a bridge builder and engineer. His first bridge worthy of notice was that over the Severn at Mountford, near Shrewsbury; it consisted of three elliptical stone arches, one of fifty-eight feet and two of fifty-five feet span. His next bridge was of iron, and crossed the Severn at Buildwas; it was of 130 feet span, being the segment of a large circle, which gave a grace and beauty to the structure, not to be found in the semi-circular bridges previously constructed. From this time iron became more general in the construction of bridges, and its use enabled the builder to reduce the number of piers, and thus to give greater facilities for the passage of floods and the free navigation of rivers. Telford showed great merit in his improvements of these structures, in the various elegant bridges which he subsequently erected.

Amongst the boldest designs of this kind were the colossal cast-iron bridge proposed to be erected over the Thames, and the wire bridge of one span of 1000 feet, and two side spans of 500 feet, designed to cross the Mersey at Runcorn Gap. Neither of these were executed, but Telford has left splendid monuments of his skill in the

Menai and Conway Suspension Bridges, with many others, both of stone and iron, which establish his position as one of the leading engineers of his time.

In the construction and improvement of canals and harbours, Mr. Telford was equally successful; and we may instance the Gotha Canal in Sweden, the Caledonian Canal, and several others of nearly equal importance at Birmingham, Glasgow, Paisley, &c., as examples of his skill. To these works must be added his improvements of the harbours of Aberdeen, Dover, and the Clyde, and the new outfall of the North Level Drainage. Telford's name is also associated with some very important works of road-making, and in this department of engineering he is without a rival. Before the introduction of railways the means of transit were brought to a high state of perfection by the improvements of the turnpike roads; and the new system of road-making, first introduced by Mr. M'Adam, was extensively carried out upon sound principles of construction by Telford. Most of us will remember the perfection of stage-coach transit, antecedent to 1830, and the bustle and activity created in every little town along the great thoroughfares of the kingdom, by the arrival and departure of the mail and stage coaches. The admirable working of this system, which created so much astonishment in the minds of foreigners, owed much of its success to the sound principles of road-making, solid foundations, smooth surfaces, and effective drainage, carried out by Telford.*

In closing this sketch, I must not omit to notice the many excellent qualities of Telford's private character, and of these I can speak from personal acquaintance. He united

* The smooth and beautiful roads in the Highlands of Scotland were executed by the late Mr. Mitchell and his son, the present intelligent engineer, under the direction of Mr. Telford.

to a mind endowed with philosophical acquirements great benevolence and goodness of heart, which rendered him accessible to all who required his assistance; and the young aspirant after knowledge was sure to find an encouraging patron and noble example in Thomas Telford. He was succeeded in his professional career by Mr. James Walker, whose works in harbours, docks, &c., are so well known.

STEAM NAVIGATION, of which we have not yet spoken, is of much greater antiquity than most persons suppose. It is said that Dr. Papin suggested the use of steam to work paddle-wheels as early as 1690, and that he actually propelled a vessel on the Fulda by one of Savery's engines in 1707. How far this statement is entitled to credit I am not prepared to say; but Jonathan Hulls took out a patent in 1736 for a boat with paddle-wheels over the stern; and the Compte D'Auxeron and M. Perrier are stated to have made experiments upon a paddle-wheel steamboat in 1774; but, like most other premature inventions, these remained unproductive for many years.

In 1788, Mr. Miller, of Dalswinton, assisted by Mr. Taylor, then in the capacity of tutor in his family, made the first certainly successful trial of a steam-boat worked by an engine and paddle-wheel. The boat was a twin boat with the wheel in the middle, and driven by an engine with a cylinder of four inches diameter. This engine is, I believe, in the Government Museum at Kensington Gore. The following is the account of the experiment which appeared in the newspapers at the time:— "On the 14th instant a boat was put in motion by a steam-engine upon Mr. Miller's piece of water at Dalswinton. That gentleman's improvements in naval affairs are well known to the public. For some time past his attention has been turned to the application of the steam-engine to the purposes of navigation. He has now accomplished, and evidently shown to the world, the practica-

bility of this by executing it upon a small scale. A vessel twenty-five feet long and seven feet broad, was on the above date driven with two wheels by a small engine. It answered Mr. Miller's expectations fully. The engine used is Mr. Symington's new patent engine."*

This experiment led to a second essay by the same parties upon a larger scale. In the autumn of 1789 a boat was fitted up upon the Forth and Clyde Canal, and engines with 18-inch cylinders placed in it; on trial a speed of six to seven miles an hour was easily obtained. From some unaccountable cause Mr. Miller neglected to patent his invention, after having established at very great cost, the practicability of employing steam as a motive power in the propulsion of vessels.

The next most important experiment upon this subject was made in 1801–2, when Lord Dundas, of Kerse, with the assistance of Symington, built a boat for towing vessels upon the Forth and Clyde Canal. This vessel, named the Charlotte Dundas, obtained, with an engine of twenty-two inches cylinder and four feet stroke, an uninterrupted speed of seven miles an hour.

"In this vessel (fig. 34), there was an engine with the steam acting on each side of the piston, working a connecting rod and crank, and the union of the crank to the axis of Miller's improved paddle-wheel. Thus had Symington the undoubted merit of having combined together for the first time those improvements which constitute the present system of steam navigation."†

The early experiments of Miller, Taylor, and Symington, of this country, had scarcely become known at the time of the realisation of Watt's great discovery of the double action condensing engine, when the enterprising Americans began to attempt the application of steam to the pro-

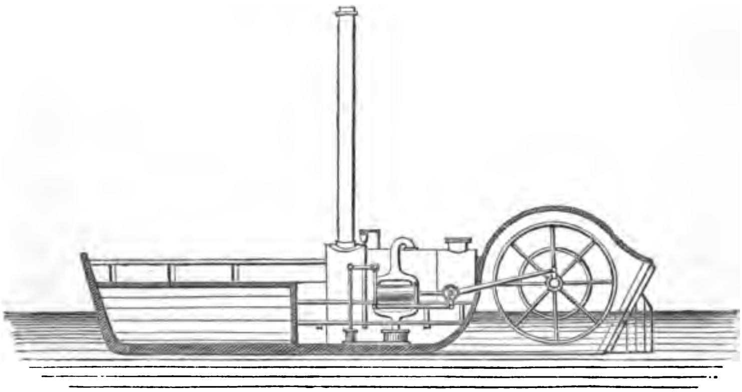
* Bennet Woodcroft's History of Steam Navigation, p. 36.

† Bennet Woodcroft, p. 54.

pulsion of vessels. Finch, Rumsey, and Stevens were early in the field, but it was reserved for Fulton to give the crowning effort to all previous experiments by the introduction of his first boat on the Hudson in 1807–8, where it plied between New York and Albany as a regular packet-boat. From that time the Hudson has been the scene of most of the improvements in steam navigation that have taken place on the American waters.

From the period of these experiments down to the present time a succession of improvements have led to

Fig. 34.



the employment of steam-vessels to so great an extent as to change the relations of all countries, and to establish a new era in the history of navigation. The paddle-wheels of steamers have undergone several modifications, such, for instance, as Morgan's and Galloway's patent wheels, with a vertical rise and dip of the float boards; but the greatest advance which has yet been made is the introduction of the screw-propeller. There are many claimants for this invention, but none are better

entitled to the credit of practically introducing it than Captain Smith and my friend, Mr. Bennet Woodcroft. As early as 1830 I witnessed the performance of Mr. Woodcroft's working model, with a screw on each side of the vessel, and since then he has introduced the variable pitch, and improvements for connecting and detaching the screw when the vessel is under canvass. Captain J. P. Smith, however, was the first to apply the screw in a practical form, and I well remember the trials of the "Archimedes" on the Thames some twenty years ago, the results of which took the nautical world by surprise, and created no small degree of alarm in the minds of the advocates of non-progression and let-well-alone. Now the screw has become one of the most important instruments of propulsion both in vessels of war, where the protection of the implements of motion from injury by cannon shot is absolutely requisite, and also as a principal or auxiliary in our mercantile marine.

What great advantages we have received from this extension of steam power! How much the danger to life and property has been diminished! What certainty and despatch have been secured in spite of wind and tide, in the conveyance of intelligence, the transport of troops, and the interchange of natural and manufactured products! But looking onwards from these realised benefits, we must admit that the same power which moves vessels of great size with so much celerity, and gives so many advantages to the country in its commercial relations, is nevertheless a source of danger as well as security, in the facilities it affords for sudden incursions by hostile armaments, at various points along our unprotected coasts. The extensive use of steam in the Navy will necessitate an entirely new system of tactics, and the sooner the Government is alive to the existence of the danger from this source which our own improvements in marine propulsion have created,

the sooner we shall be prepared to repel aggression from whatever quarter we may be assailed. It is well known that every change in our habits and conditions of life is sure to be resisted "tooth and nail" by all those who wish to maintain the dignified position of "as you were." This standing at ease is out of fashion now-a-days, and we must either move on, or be left a stranded wreck in the tide of progress. I am most desirous to impress these facts upon you, and upon the authorities of the Admiralty, where so much must be done in initiating a new system of naval tactics before we can be prepared for the exigencies of a maritime war, possibly not far distant, and which, whenever it arrives, will have to be maintained by the agency of steam. Steam rams may or may not come into use, but it is certain that increased steam power and increased speed in the Navy may give to the nation that ascendency in maritime affairs which more than anything else is its greatest security considered in its relations with other countries. I am, therefore, most anxious to see our own Navy foremost in power and perfect in discipline, so that England may long continue in pride and glory the mistress of the seas.

Iron Shipbuilding.—This is a subject with which I have been intimately connected for many years, and to the advance of which I have had the honour of contributing. I was the first to commence iron shipbuilding in London, and, I believe, was the second to send an iron vessel to sea. From 1829–30 to 1848 I built upwards of 120 iron vessels, some of them upwards of 2000 tons burden, and nine of which were built in sections at Manchester, and the remainder on the banks of the Thames at Millwall. If time permitted I could give you the whole history of this important branch of industry, and show from what small beginnings one of our largest branches of industry has sprung. Suffice it to observe that in 1829–30 Mr. Hous-

ton, of Johnstone, near Paisley, launched a light gig-boat on the Ardrossan Canal for the purpose of ascertaining the speed at which it could be towed by horses with three or four persons on board. To the surprise of Mr. Houston and the other gentlemen present it was found that the force of traction, or labour the horses had to perform in towing a light boat of this description, was much greater at a velocity of six or seven miles an hour than at nine miles an hour. This anomaly in the trials was puzzling in the extreme, and it was in this stage of the experiments that I was requested by the Council of the Forth and Clyde Canal to visit Scotland and institute a series of experiments with light boats in order to determine the law of traction, and to clear up the anomalies of Mr. Houston's experiments.

The Forth and Clyde experiments commenced in the spring of 1830, first with wooden, and ultimately with light iron boats; and these experiments led to the construction of iron vessels upon a large scale and on an entirely new principle of construction, with angle iron ribs and wrought iron sheathing plates. With the exception of these iron canal boats the first iron vessel was made in 1822, and was navigated from this country to Havre de Grace by Admiral, then Captain, Napier, with the intention of employing it upon the Seine. The next iron vessel was built by myself, at Manchester, and another (the Alburka) by Laird, both of which were completed, and went to sea in 1831. From that time to the present iron vessels have been built of all sizes, from the smallest wherry up to the Leviathan of the Great Eastern Navigation Company.

The experiments on the Forth and Clyde Canal occupied a series of years, and no less than five experimental vessels were made at a cost of several thousand pounds; the results not only elucidated the phenomena of diminished

traction at high velocities, but led to a new construction of iron vessels, and other structures, of which wrought-iron formed the whole or the principal material. These experiments, however, did not accomplish the ardent wishes of the proprietors of canals, who at that time were alarmed at the progress of railways, in consequence of the competition at Rainhill, in the same year, for the best locomotive engine. It was then railways *versus* canals; and although in the experiments we obtained a velocity as high as fourteen miles an hour with a light boat drawn by horses, we never could obtain more than seven and a half to eight miles by steam.

Iron Houses.—Iron as a building material is not confined to ship-building alone; it is employed in almost every other department of useful art, and is now largely applied to the construction of houses. When cast and wrought-iron are united in these constructions, they form some of the most convenient and beautiful combinations possible. All the forms of highly decorative architecture, cornices, mouldings, &c., can be produced in castings from pattern models; and these united together with plates either corrugated or plain, and securely riveted to a frame-work of angle or T iron, give to a house of this kind erected upon a basement of stone or brick the characteristics of a cheap and handsome edifice. Warehouses, shops and private residences are now built in this way, and I might instance the large edifices recently erected in New York, Glasgow, and other places, where the whole of the street façade is constructed of iron, and that in a style of architecture perfectly symmetrical and in harmony with the finest stone buildings in either city.

As a material for street architecture, it is admirably adapted, from its powers of repetition and security from fire; and I am one of those who have great faith in iron walls and iron beams, and although I have both spoken

and written on the subject, I cannot too forcibly recommend it to public attention. It is now twenty years since I constructed an iron house with the machinery of a corn mill for Halil Pasha, then Seraskier (commander-in-chief) of the Turkish army at Constantinople. I believe it was the first iron house built in this country, and was constructed at the works at Millwall, London, in 1839.

IRON BRIDGES form another class of constructions in which, of late years, iron has been most extensively employed, both in its cast and malleable conditions. Iron is employed for bridges on three principles, the suspension chain, the horizontal beam or girder, and the arch. The earlier bridges were of cast-iron, and were erected in the form of large semicircular arches, sustained by heavy abutments, formed of masonry. The introduction of cast-iron in this form dates from a period not more remote than 1779, when Mr. Pritchard, with the aid of Messrs. Darley and Reynolds, constructed a bridge over the Severn at Colebrookdale, and even in this first attempt it indicated its superiority over stone for large spans. From that time to the present a very large number of cast-iron arched bridges have been erected, both for railway purposes and for ordinary road traffic, but none of them have exceeded 250 feet span.

The introduction of railways created a demand for a great number of bridges of small span for crossing roadways and canals, in cases where it was requisite that the depth of the bridge should be as small as possible. For spans of forty to fifty feet, this demand has been admirably met by the introduction of cast-iron beams, with a perfectly horizontal soffit, but for larger spans they are objectionable and dangerous. The best form for larger spans, where cast-iron is required to be used, is the flat arch with a versed sine of about 1-20th the length of the chord. This description of girder partakes of the properties of the beam as

well as the arch; it does not depend entirely upon voussoirs, as an arch of equilibrium, being partly retained in form by the unyielding nature of the abutments resisting the thrust of the arch; and from its connection at the joints by bolts, it becomes a beam with a large camber, supporting the load by its resistance to compression and extension, along the top and bottom flanches.

The true development of girder bridges was not, however, attained, until the experiments in connection with the erection of the Conway and Britannia tubular bridges, determined the true forms and proportions in which wrought-iron should be distributed to resist the enormous strains to which bridges of wide span are subjected. Wrought-iron as a material for bridges is free from the objections which attach to cast-iron; it is uniform in strength and texture, of well-ascertained properties, entirely free from those irregular strains to which cast-iron is subject from unequal contraction in cooling; and, moreover, its tensile and compressive strengths when arranged in suitable forms do not bear so great a disproportion to each other as is the case with cast-iron. Hence the introduction of wrought-iron for railway and other structures in which certainty of construction and security from danger are required, has proved to be one of the most important eras in the history of bridges.

It will not be necessary to trace the origin and course of the experiments which were instituted to determine the proper form and dimensions of the tubular bridges which cross the Conway and the Menai Straits. Suffice it to observe, that in the construction of the Chester and Holyhead railway, it was found necessary, in order to comply with the demands of the Admiralty (who watched over the interests of the navigation of the Straits), to erect a bridge of colossal dimensions, having four spans, and leaving a clear opening on each side of the centre pier of 460

feet, with an elevation of 100 feet from the level of high water to the bottom of the bridge.

This could not have been accomplished by the ordinary applications of iron, such as cast-iron arches or chain bridges; the former not giving sufficient height above the water-level, and the latter from their flexibility being unsuited for the support of railway trains. It was ultimately conceived that huge wrought-iron elliptical tubes, supported by chains, through which the trains should pass, might meet the demands of the Admiralty. But before this conception was adopted, a laborious series of experiments was instituted, which pointed out the defects of the elliptical tube, gave the true principle on which such a structure should be designed, determined the formulas for calculating its strength and proportioning its parts, and thus established an entirely new system of construction. The Britannia Bridge was then erected, and with its companion at Conway remains with hundreds of others composed of the same material and upon the same principle of construction, memorials of the accuracy of the investigations which led to the introduction of wrought-iron in this and other systems of adaptation. The total length of each tube of the Britannia Bridge is 1524 feet; height in the middle, 33 feet; and width, 14 feet 8 inches. The total weight of iron amounts to the enormous quantity of 10,570 tons. The Conway Bridge is of smaller dimensions, consisting of one span of 400 feet, crossed by two tubes, each 424 feet long, 25 feet 6 inches in height at the middle, and 14 feet 8 inches wide. The weight of iron amounts to 2892 tons.

Since the erection of these bridges wrought-iron has been extensively employed for girder bridges of all spans up to 500 feet, and it is capable of being extended if necessary to spans of 1000 feet.

Prime Movers.—From 1784 to 1815, the cotton trade, with some fluctuations, made considerable progress;

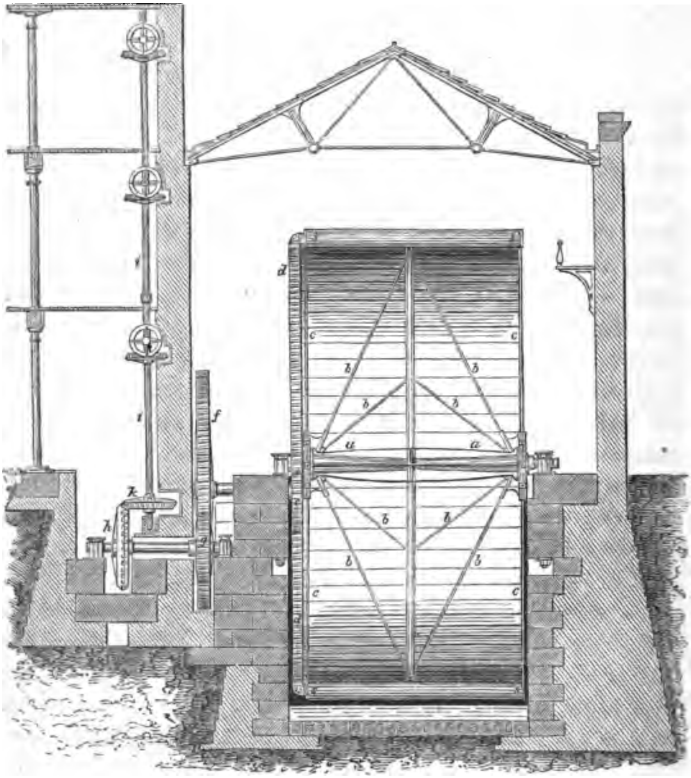
but the steam-engine was comparatively little appreciated or applied. In the earlier stages of manufacturing industry, the mills were erected on streams with waterfalls of sufficient power to turn their machinery. Hence the distribution of the mills over the country—as at Cromford, Belper, Bakewell, and Darley. At the commencement of my own career this was the condition of some of the largest cotton works in the kingdom. At the present time water, as a motive power, is only of secondary consideration, nineteen-twentieths of the mills now in existence being driven by the steam-engine. I well recollect the skill, beauty, and solidity with which the water-wheels were constructed when water was generally the motive power. The best of these wheels were made entirely of iron, on the principle of suspension, the arms not exceeding two or two and a quarter inches in diameter, and the power being taken off from the periphery by a pinion on the loaded side of the wheel.

Mr. T. C. Hewes is justly entitled to the merit of these improvements, and was assisted by the late Mr. Strutt, of Belper. The most important of the recent improvements of the water-wheel are, however, the ventilation of the buckets and the use of cotters in the place of nuts and screws for fixing the arms and braces to the centre flanges of the wheel.

Fig. 35 represents a large water-wheel of iron, of the best modern construction, and erected at Gefle, by W. Fairbairn and Sons, near Stockholm, in Sweden. This wheel is 40 feet in diameter, and 20 feet broad, or 18 feet between the shrouding plates. It is supported on the large cast-iron axis, *a a*, by means of the small wrought-iron arms, *c c*, and braces *b b*, on which the wheel is in fact hung or suspended. The arms are attached to the shrouding plates *s s*, and at the other end to the main centre, to which they are fixed by gibs and cotters. The braces are similarly attached diagonally between the main centre and

the middle ring of cast-iron. Around the periphery of the wheel is fixed an internal spur-wheel, *d*, cast in segments, into which gears the pinion *e*, so as to afford the highest velocity direct from the water-wheel; this

Fig. 35.



again is further increased by the spur-wheel *f* and pinion *g*, and bevel wheels *k* and *h*, which transmit the power to the upright shaft *i* of the mill.

There is therefore (1.) the water-wheel segment, *d*, with 324 teeth of $4\frac{3}{8}$ inch pitch, and 14 inches width, giving 2 revolutions per minute, geared into,—

(2.) Pinion *e*, 6 feet 1 inch diameter, giving 12·3 revolutions of cross shaft.

(3.) Spur-wheel *f*, 20 feet diameter, geared into pinion *g*, 5 feet 6 inches diameter, giving 43 revolutions per minute to second cross shaft.

(4.) Bevel-wheel *h*, 7 feet 8 inches, geared into bevel wheel *k*, 4 feet $1\frac{1}{2}$ inches, giving 80 revolutions of upright shaft *i* of mill.

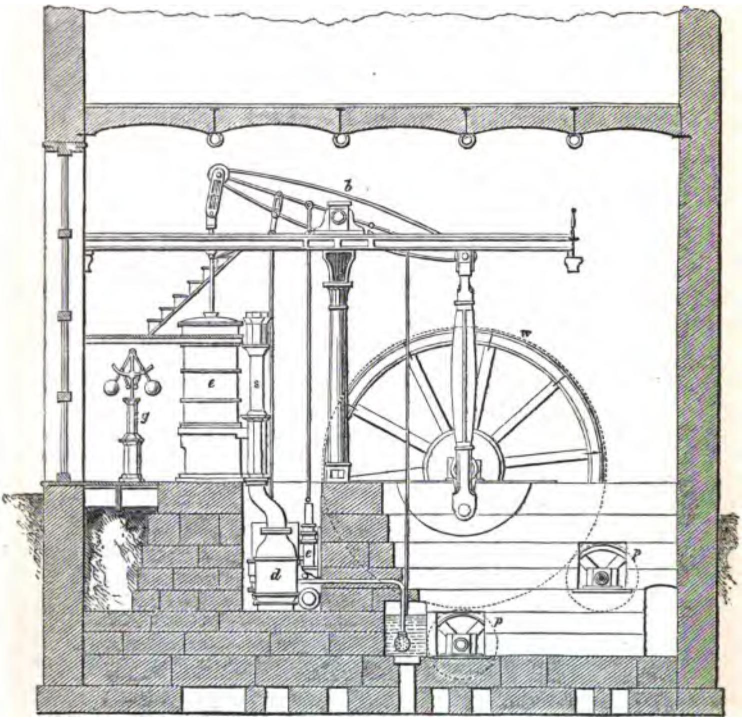
The power of this wheel is equivalent to 150 horses.

Figs. 36 and 37 illustrate the construction and details of two pairs of condensing beam engines of 400 total nominal horses power, employed in driving the machinery for preparing spinning and weaving alpaca fabrics in the extensive mills of Titus Salt, Esq., of Bradford. They may serve as types of the present development of steam prime movers. These engines are arranged in two large engine-houses on either side of the front entrance to the mill buildings, and they are supplied with steam from ten boilers placed in a boiler-house beneath the surface of the ground, and a short distance in front of the mills. Fig. 36 shows a side elevation of one of these engines, giving a general view of the arrangement of the parts, and fig. 37 a cross section. The power generated in the cylinder *e*, and transmitted through the working beam *b b* to the large fly-wheel *w*, 24 feet in diameter, is taken direct from its circumference by the pinions *p p*, which give it off at the required velocity to the shafting of the mill. This arrangement has become very general for factory engines, and is the most effective and economical plan for generating at once the high speed which they require.

The valves are of a peculiar construction, being a modification of the double heat or equilibrium valve invented

by Mr. Hornblower, and they have the merits of affording any required amount of expansion, with a rapid cut off, and absence of wire drawing, and a fully open passage to the condenser during the whole of the stroke. In ordinary working these engines give 900 actual horses power,

Fig. 36.



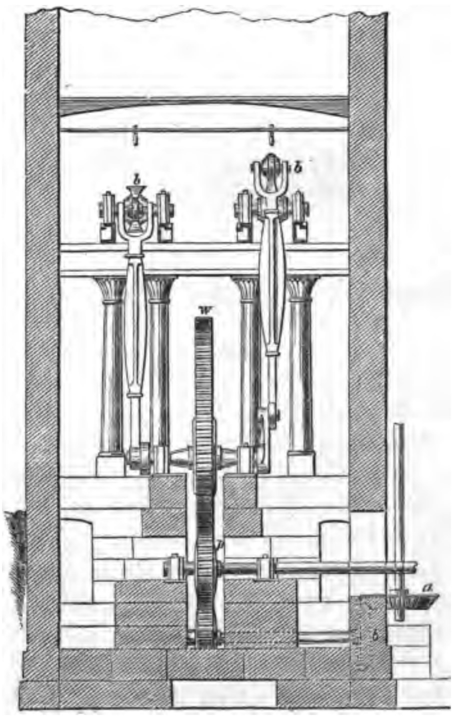
although they are capable of considerably more. They burn 16 tons of slack coal per day.

The following dimensions are given that they may be compared with the engines selected for illustration in my former lecture, and the progress made in mechanical

science since the time indicated by the more early developments in practical science:—

Diameter of cylinder . . .	50 inches.
Stroke	7 feet.
Length of beam	21 feet 7 inches.
Diameter of fly wheel . . .	24 feet.
Pressure of steam in boiler . .	20 lbs. per square inch.
Nominal power of each engine .	100 horses.
Indicated or working power, at 33,000 lbs. raised one foot high in a minute, or the actual power given out by each engine, is equivalent to	300 horses.

Fig. 37.



MILLWORK.—In the machinery of transmission as great improvements have been made as in any other department of practical science, and I have to attribute my own success in life to the changes which it has been my privilege to introduce into this class of machinery. When I first entered Manchester the mills were driven by large square cast-iron shafts (fig. 38), on which huge wooden drums revolved at the rate of about forty revolutions per minute; and the couplings were so badly fitted that you might hear them croaking at some distance from the mills. Now, the wheels and shafts (fig. 39) are

Fig. 38.

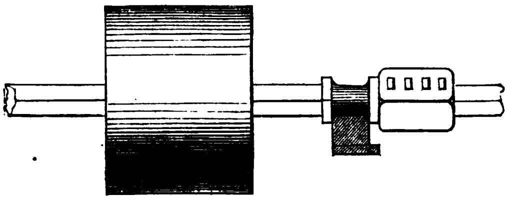
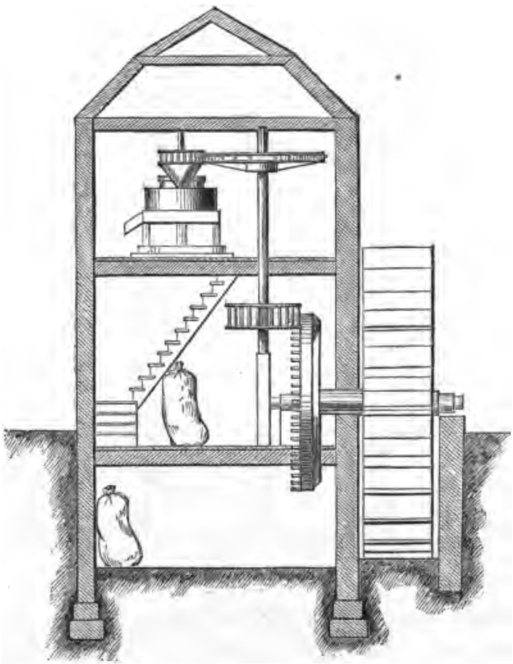


Fig. 39.

executed with an almost mathematical precision, and instead of huge drums four or five feet in diameter, revolving thirty or forty times a minute, we have small light turned pulleys, keyed upon polished iron shafts, revolving at 120 to 200 times per minute. In figs. 38 and 39 the change is apparent, as both shafts are calculated to perform the same amount of work, notwithstanding their apparent difference in size and strength. The introduction of lighter shafting led also to the simplification of the hangers and fixings by which it is supported, and to the

introduction of the half-lap coupling, so well known to millwrights and engineers. The fly-wheel of the engine was also converted into a first motion by the formation of teeth on the periphery (*w*, figs. 36 and 37), which resulted in a considerable saving of cost and power. This system was at first condemned by some of our leading engineers, and it was with difficulty that I overcame the opposition they created; indeed it was not until a wheel of thirty tons weight for a pair of engines of 100-horse power each was erected, that the prognostications of failure entirely ceased. The principle has now become general wherever steam is employed as a motive power in mills.

Fig. 40.



Corn Mills.—Figure 40 is a sketch of a corn mill erected in 1730, and clearly illustrates the condition of millwork and gearing at that time. Figs. 41 and 42 exhibit

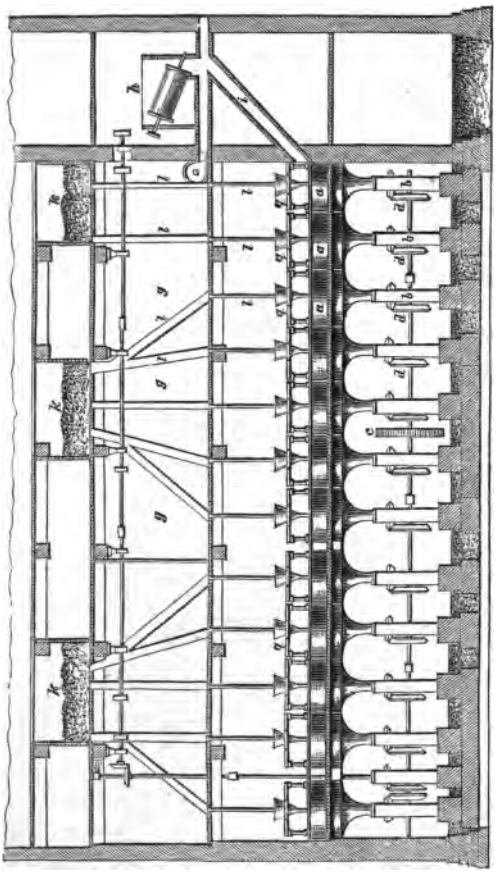
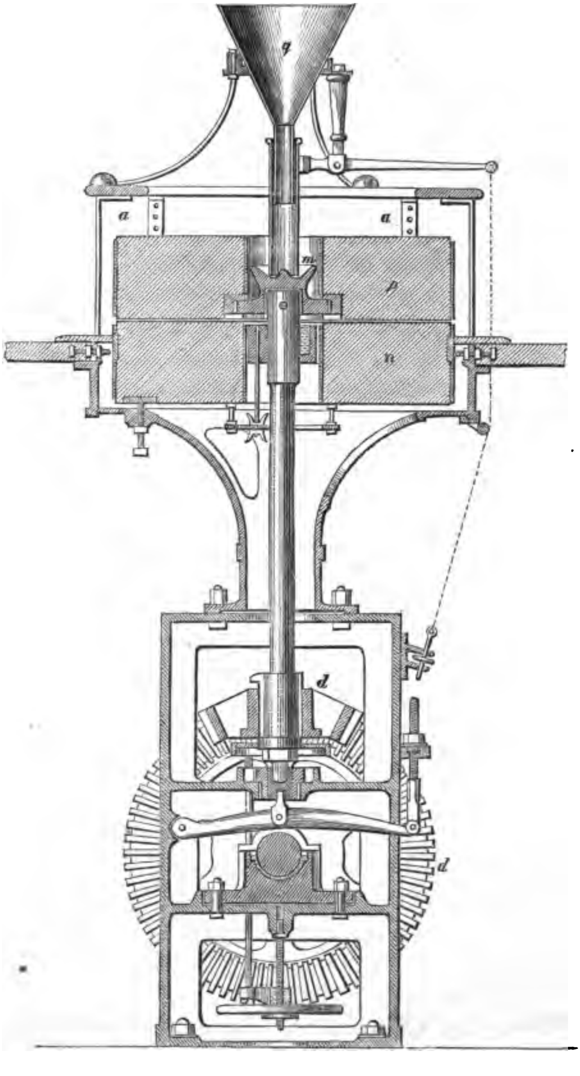


Fig. 41.

the present condition of this important branch of the millwright's art. As in most English mills of the present

Fig. 42.



day, it will be seen that the pairs of stones, twelve in number (*a a a*) are arranged in a single line, enclosed in iron cases, and supported on strong iron framing (*b b*). The power required to drive the mill is obtained from a steam-engine, the fly-wheel of which gears into the pinion *c*, and the motion is then distributed on each side to the stones by the bevel wheels *d d d*. The wheat, as it is brought to the mill, is first delivered in its uncleaned state into the wheat garners *g g*, situated upon the machine flat. From these it is passed by means of Archimedean screw creepers to the wheat screen or smut machine *h*, whence it falls into an elevator through the spout *i*, which raises it again to the upper story; it is thence distributed by another creeper into the clean wheat garners *k k k*; from these it passes by the feed pipes *l l l*, to the feed hoppers of the stones *q*, and after being ground to flour is raised again by a creeper and elevator to the machine floor, where it passes through the dressing and bolting machinery. Fig. 42 is a section of a pair of stones with its driving and feeding apparatus, stone case (*a*), rhind (*m*), bed stone (*n*), and running stone (*p*). Such a mill as this will grind 70 to 90 bushels of wheat per hour, according to the dryness of the grain employed.

RAILWAYS.—In tracing a faint outline of the progress of practical science and industrial art, we have yet to notice one of the most important improvements that has ever occurred in ancient or modern times. The railway system, combined with the locomotive engine, is both a discovery and an invention, and the introduction of these developments, contemporaneously with the progress of steam navigation, has changed the destinies of nations, and brought the most distant and barbarous races within the reach of civilisation.

Railways are of comparatively remote origin, having been in use for upwards of two hundred years, as may be

seen from records of the collieries of Northumberland, dating from the time of Charles the Second. I still retain a distinct recollection of being employed, in 1807, at the Percy Main Colliery, in making patterns for cast-iron fish-bellied rails and these were amongst the first, if not the first, iron rails introduced as a substitute for wood. For many years after this cast-iron was employed, and it was not until the locomotive rendered a tougher material requisite that wrought-iron was substituted for cast. The form of section of these rails was at first defective in the extreme, but they have since been constructed on sounder principles, and of stronger and heavier proportions.

Iron roads, however, are of little value without the locomotive engine, and the latter we owe exclusively to the marvellous developments of the last forty years. Imperfect and premature attempts were made to introduce steam as a motive power for carriages more than a hundred years ago; and Mr. Murdock, of Soho, made a working model of a locomotive-engine at the close of the last century, which I have myself seen travelling on a circular railway at the rate of five miles an hour. Mr. Trevietheck also made a locomotive-engine in 1804, which was mounted on a carriage with four wheels, and worked on an iron tramway at Merthyr Tydvil, dragging waggons loaded with fifteen tons of iron for a distance of nine miles in rather less than two hours. Mr. Blenkinsop, however, introduced the first really successful engine at Leeds in 1812. This engine worked for many years, and in order to prevent the wheels from slipping, racks were introduced upon the rails with large hollow cogs, into which the corresponding teeth on the wheels worked. This contrivance, however, was soon abandoned, the adhesion of the wheels to the rails being found sufficient to prevent slipping.

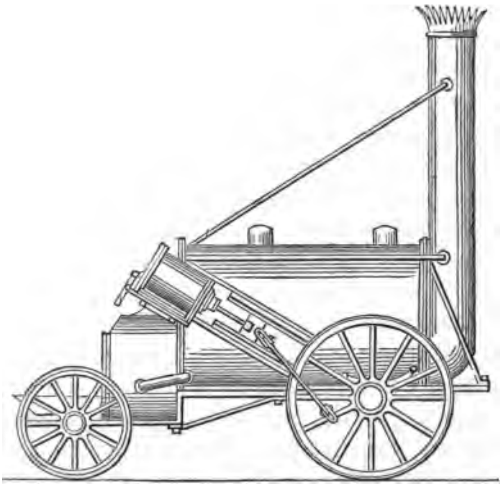
The success of Blenkinsop's engine induced the coal-owners of Newcastle to make a similar experiment on their tramways, with a view of dragging the empty waggons up the inclines in this way. It was in these and subsequent experiments that George Stephenson first became known, whose skill and exertions have since so deservedly earned for him the title of the "Father of Railways." He was one of the most courageous and persevering engineers this country has produced. Endowed by nature with great powers, although comparatively uncultivated and uninstructed, he never lost sight of the object of his pursuit, and his never tiring energy of character carried him successfully through difficulties which would have crushed more ordinary men. George Stephenson was never afraid of work, and by the constant exercise of a sound judgment, combined with indomitable perseverance, he was led to the honourable accomplishment of the great work he had to perform. Such was his character when I first worked an engine for him on the Tyne, and such was the man when I last parted with him a few weeks before his death.

Time will not permit me to enter into detail on the progress of the locomotive engine, in all the changes and transformations through which it has passed. Suffice it to observe, that Mr. Jonathan Foster, of Wylam, near Newcastle, was among its first improvers; he connected all the four wheels by spur gear, first dispensing with the tooth work on the wheels and rails. Stephenson then altered the positions of the cylinders and wheels, improved the flues and furnaces of the boiler, and introduced the blast into the chimney, one of the most important elements in the success of the locomotive. A long and angry contest has been carried on in the journals as to the priority of the invention of the blast, but I have every reason to think it belongs to Stephenson, as I have heard him claim

its introduction, and have no reason to doubt his veracity, or that he was quite equal to the task. Mr. Trevithick is, however, said to have introduced the exhaust or waste steam pipe into the chimney in 1806, to obviate the noise occasioned by the steam rushing into the air, and he is reported to have found that a greatly increased draught and a diminished consumption of smoke and fuel resulted from this modification.

The trial of locomotives at Rainhill, in 1830, at which I was present, developed entirely new principles in the action of the steam engine, and indicated by its unexpected results the high velocities which would follow the employment of

Fig. 43.



steam power upon railways, although at that time neither Mr. Stephenson nor any one else had any adequate conception of the benefits which the extension of railways has already secured. It was the general belief of those

interested in the trial that a speed of ten or twelve miles an hour was the utmost that could be obtained, although an able writer in the *Scotsman* had argued some months before that the only limit to speed was the power of the engine. The blast of waste steam in the chimney, the introduction of small tubes in the boiler, as suggested by Mr. Henry Booth, and the enlargement of the furnace, were the great improvements of the locomotive engine, and were all exhibited in the "Rocket" of George Stephenson. This engine, which is shown in fig. 43, was the successful competitor at the Rainhill trial. From 1830 to the present time little or no change has been made in these principles of construction, but great modifications of the arrangement and of the details have been effected, and with these the locomotive is now one of the most perfect and effective machines ever constructed.

In my former address I gave an estimate of the total horse-power of the locomotives of the United Kingdom. I will now give you some idea of the energy of a single locomotive engine. When travelling at forty miles an hour, with a pressure of 90 lbs. per square inch on the piston, it will be found that a large locomotive exerts a force equivalent to about *seven hundred horses;* and these data, so well calculated to astonish the unreflecting, should make us proud of the country where such triumphs have been achieved. Had it not been for Mr. Stephenson's unflinching energy in maintaining his opinions, single-handed, against large majorities, the country and the world might have remained for many years without the advantages which our railway system has conferred upon all classes of the community.

It is an agreeable task to enumerate the merits and pay tribute to the memory of men who have done so much for their country. The name of George Stephenson will stand beside those of Brindley and Telford and Watt, amongst

the pioneers of progress by whose aid mechanical science and art have attained their present high state of perfection.

In conclusion, I can only allude in passing to one of the greatest wonders of our age, the electric telegraph; and although not, strictly speaking, within the province of mechanical art, it may safely be included among the achievements of the last half century of which we have been speaking. The phenomenon of the electric current, when practically employed in the transmission of intelligence, cannot be viewed in any other light than the crowning triumph of the age; and it must ever be a subject of congratulation to us that in our lifetime the spark of heaven—if I may use the expression—was commissioned to be our swift obedient minister in conveying thought and intelligence from man to man (irrespective of distance or of time) to the remotest parts of the earth.

LECTURE V.

THE STRENGTH OF IRON SHIPS.

[Read before the Polytechnic Institute in Liverpool, and at the opening Session of the Institute of Naval Architects in London.]

It is nearly thirty years since the construction of *iron ships* for sea-going purposes was first entered upon; and I believe I was the first to show, in conjunction with Messrs. John and McGregor Laird of Birkenhead, the superior strength and security of iron vessels. After a long series of experiments in the construction of different forms and dimensions, it was found that the resisting powers of an iron vessel, when properly constructed, could be depended upon for navigating the open sea, and was much better calculated, as respects lightness, capacity for cargo, &c., than one composed of the best English oak. These considerations induced Messrs. John and McGregor Laird and myself to commence iron-ship building on a large scale, and thus to realise an expensive and laborious series of experiments on the value of these constructions. Hence I founded the works now occupied by Messrs. John Scott Russell and Co. at Milwall, London, in which establishment (carried on under my own direction from 1835 to 1848) upwards of one hundred vessels were built; and the applicability of iron to the purposes of naval architecture was then and has since been fully demonstrated in the construction of several splendid steamers, such as the *Great*

Britain, the *Persia,* and the *Great Eastern,* and also of sailing vessels of very large tonnage.

But although considerable improvements have been introduced in the design and construction of iron vessels during the last quarter of a century, the subject does not seem to have been theoretically or practically investigated to the extent to which the importance of the subject so justly entitles it. My own experiments related chiefly to the strength of the material itself, its distribution, and the value of different kinds of riveted joints as compared with the solid plate.

Nothing has, however, been done, so far as I know, in determining the strength of an iron ship *en masse;* and the object in view in the present paper is to inquire into the strength of iron vessels as they have been and are now constructed, and to ascertain if there exist any hidden weakness which may be remedied by a more judicious distribution of the material.

Of late years it has been found convenient to increase the length of steamers and sailing vessels to as much as eight or nine times their breadth of beam; and this for two reasons: *first,* to obtain an increase of speed by giving fine sharp lines to the bow and stern; and, *second,* to secure an increase of capacity for the same midship-section, by which the carrying powers of the ship are greatly augmented. Now, there is no serious objection to this increase of length, which may or may not have reached the maximum. But unfortunately it has hitherto been accomplished at a great sacrifice of the strength of the ship. Vessels floating on water and subjected to the swell of a rolling sea — to say nothing of their being stranded or beaten upon the rocks of a lee shore — are governed by the same laws of transverse strain as simple hollow beams like the tubes of the Conway and Britannia Tubular

Bridges. Assuming this to be true, and, indeed it scarcely requires demonstration, it follows that we cannot lengthen a ship with impunity without adding to her depth, or to the sectional area of the plates in the middle.

If we take a vessel of the ordinary construction, or what some years since was considered the best construction, 300 feet long, 41 feet 6 inches beam, and 26 feet 6 inches deep, we shall be able to show how inadequately she is

Fig. 44.

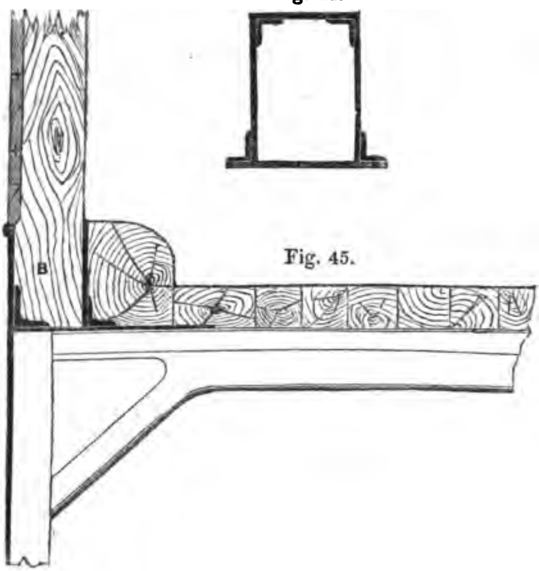
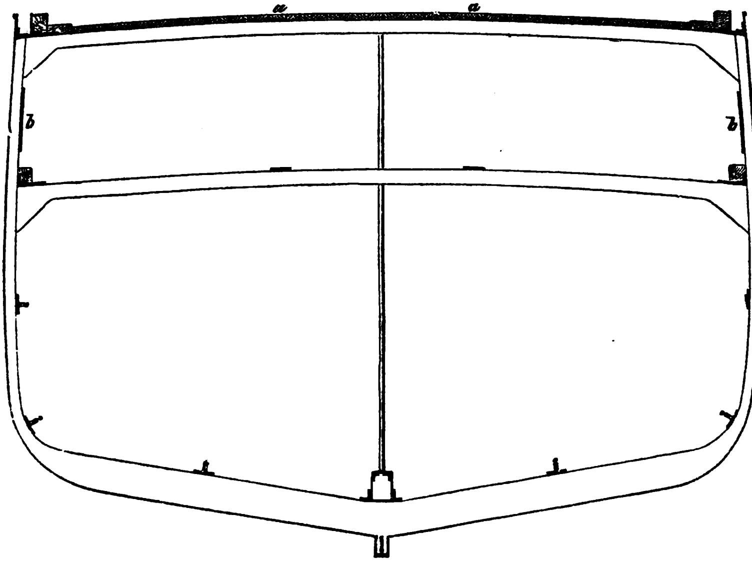


Fig. 45.

designed to resist the strains to which she would be subjected. Such a vessel would be sheathed with plates $\frac{7}{8}$ of an inch thick (working transversely from the keel to the deck on each side) for 13 feet on each side of her keel, $\frac{3}{4}$ inch plates for a distance of 10 feet 6 inches round each side of the bilge, and $\frac{5}{8}$ inch plates for the remainder to the upper deck; her keel would be 12×4 inches, with

plates on each side 2 feet wide by 1 inch thick, and in addition to this there would be a hollow stringer, similar to fig. 44, 18 × 12 inches, riveted to the angle-irons of the frames 2 feet 3 inches above the keel. At the top of the upper deck are two plates and angle-irons, forming an open box B, fig. 45, on each side 18 × 12 inches, which, together with two small stringers along the deck and two at the sides, as shown at *a a* and *b b*, fig. 46, would con-

Fig. 46.



stitute the only power for resisting a tensile or compressive strain arising from transverse flexure.

On referring to the midship-section of a vessel of these dimensions, fig. 46, it will be seen that the upper deck is not constructed so as to give stability to the ship, and is totally out of proportion with the quantity of material in the other parts of the hull. If we take a vessel such as

we have described and shown in fig. 46, and which, it must be admitted, is of inferior construction, we shall approximate nearly to the facts by treating it as a simple beam; actually a vessel is placed in this position, either when supported at each end by two waves or when rising on the crest of another wave, supported at the centre, with the stem and stern partially suspended. Now, in these positions the ship undergoes alternately a strain of compression and a strain of tension along the whole section of the deck, corresponding with equal strains of tension and compression along the whole section of the keel, the strains being reversed according as the vessel is supported at the ends or the centre. These are, in fact, the alternate strains to which every long vessel is exposed, particularly in seas where the distance between the crests of the waves does not exceed the length of the ship.

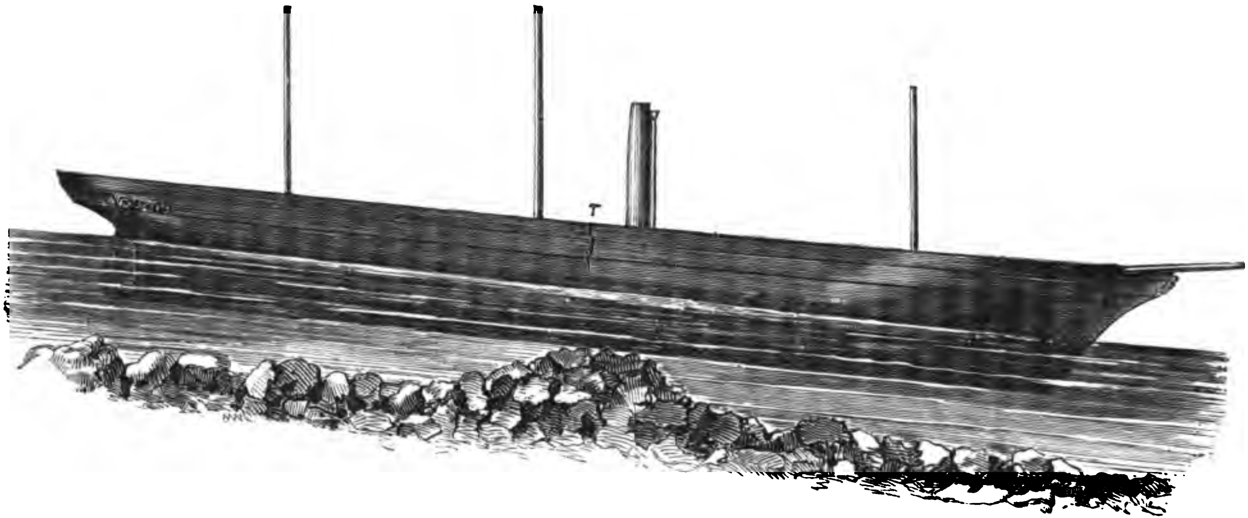
It is true that a vessel proportioned like the above section will continue for a number of voyages to resist the continuous strains to which she is subjected whilst resting in water. But supposing in stress of weather or from some other cause she is driven on a rock with her bows and stern suspended, in the position shown in the sketch, fig. 47, the probability is that she would break in two, separating at T from the insufficiency of the deck. This is the great source of weakness in wrought-iron vessels of this construction, as well as of wooden vessels when placed in similarly trying circumstances.

To prove this, let us give the vessel already described the full benefit of being considered a well-constructed beam, which indeed is more than we may expect; and applying the formula,

$$W = \frac{a\,d\,c}{l}$$

which would then be applicable, we shall find her powers of resistance comparatively small.

Fig. 47.



The sectional areas of wrought iron we shall find to be as follow:

	Inches.	Square inches.
Keel . . .	12×4 . . .	48
Hollow stringer . .	18×12 . . .	46
Sheathing . . .	$312 \times \frac{7}{8} + 252 \times \frac{3}{4}$.	462
Plates at keel . .	48×1 . . .	48
Total area of bottom . . .		604

To balance this area at the bottom, we have at the top, taking the sheathing-plates to a depth of six feet below the upper deck:

	Square inches.
Stringer-plates and open trough-plates . .	190
Side-plates, to a depth of six feet on each side .	110
Deck-planking	100
Total area of top	400

The deck-planking, which to a limited extent contributes to the resistance to a tensile strain, might be taken at one-sixth the resisting powers of iron, or equivalent to

$$\frac{41 \cdot 5 \times 12 \times 6}{6} = 490 \text{ square inches};$$

but the entire absence of longitudinal joints reduces this resistance much farther, and we have, therefore, considered the resistance of the deck-planking to be equivalent to a section of 100 square inches of wrought iron.

Now if we apply the formula for beams, we have, for the constant, $c=60$, on account of the joints being only double riveted; $a=400$ square inches; $d=$the effective depth, which, since the side-plates have been taken for a distance of six feet from the deck, could not exceed 24 feet; $l=$length$=300$ feet; hence the centre-breaking load is equivalent to

$$W = \frac{400 \times 24 \times 60}{300} = 1920 \text{ tons},$$

or in other words, a weight of 960 tons suspended from

bow and stern, apart from the vessel's own weight, would cause her to break asunder.

We may verify this calculation by another, in which the strength is calculated from different data. If we substitute for the area of the top the whole midship area of the vessel, and for $c = 60$ substitute $C = 18{\cdot}3$, we get,

$$W = \frac{1400 \times 24 \times 18{\cdot}3}{300} = 2049{\cdot}6 \text{ tons},$$

which gives a close coincidence of result with the previous calculation.

If, however, the deck-beams were covered with iron plates throughout the whole length, on each side of the hatchways, so as, by a new construction, to render the area at the deck equal to that at the bottom, we should then have for the centre breaking weight

$$W = \frac{604 \times 26{\cdot}5 \times 60}{300} = 3200 \text{ tons},$$

or nearly twice the strength given in the preceding case.

If we now consider the amount of displacement in tons in the vessel we have described, we shall find that the margin of strength is far from satisfactory. When loaded to a depth of 18 feet draught of water, the displacement would be about 177,000 cubic feet, which is equivalent to a weight of about 5000 tons for the ship and cargo. If we consider this weight as uniformly distributed, and compare it with the strength we have determined, we have,

	Tons.
Load uniformly distributed	5000
Breaking-weight with load distributed, 1920 × 2 . .	3840
Leaving a deficiency or source of weakness equivalent to .	1160

so that it is evident that if laid high and dry, in the position shown in fig. 47, she would break with $\frac{38}{50}$ or $\frac{4}{5}$ of the load which she actually carries. Under ordinary cir-

cumstances, it is true that a vessel could never be placed in such a position, unless when stranded on a lee shore, or under circumstances where each receding wave would leave her with not more than six or eight feet of water over her keel, and in these conditions she must inevitably go to pieces.

I refer to these extreme cases because our iron constructions, in which we risk so much life and property, *may* be exposed to even this degree of danger, although circumstances so critical do not frequently occur. If we might suppose material added to the deck-section, either by iron plates under the planking or in any other form, so as to give an area of wrought iron equivalent to that of the bottom, or 604 square inches, the strength would be nearly doubled, but would still be short of an adequate margin for security to resist the force of impact, as the waves lifted the vessel and dashed her again on the rocks. It may be urged that this is an extreme case; but it is an extreme such as we must guard against, and vessels ought in every case to be built of sufficient strength to secure them from failure in all the conditions in which it is possible for them to be placed.

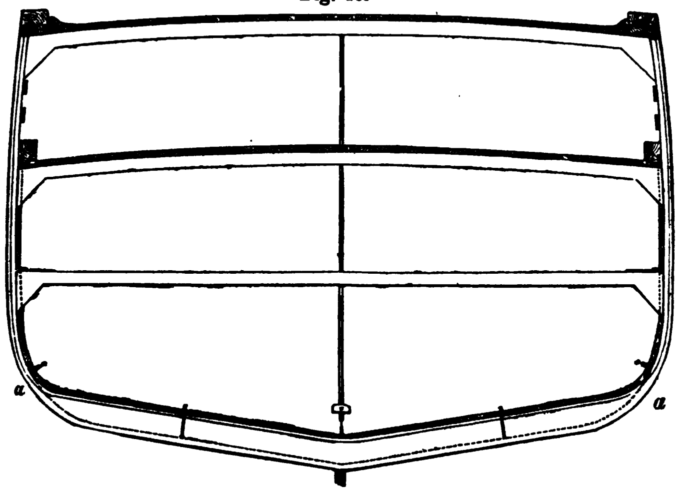
Having shown the imperfect state of our constructions from an example selected from the earlier stages of iron shipbuilding, I would now direct attention to the most recent forms of iron vessels.

It will be observed from the following diagram, fig. 48, that considerable improvements have been effected, both as regards strength and the distribution of the material, since the infancy of iron shipbuilding, when the properties of the material and the results of its combination were very imperfectly known. It is now widely different; and though still far from perfection, it is nevertheless of a character which gives greatly increased security to life and property.

Let us, for example, again take a vessel of the present build, and compare it with that of its predecessor of ten years ago, which I have already described.

Fig. 48 is the cross midship-section of a vessel of the present build, and clearly shows the improvements which

Fig. 48.



have been effected. The sectional areas of the upper deck of this vessel, which is of the same size as the preceding, are as follows:

	Square inches.
Open trough-plates on deck, and plates on each side, as before, to a depth of six feet under the deck .	. 176
Stringer-plates	. 165
Add to this, as before, for timber of decks .	. 100
Total area	. 441

where the area is larger than before, and the strength, although still deficient on the deck, would be increased from 3800 to 4200 tons, which is much in favour of the security of the ship.

Taking another vessel (fig. 49) of still more recent con-

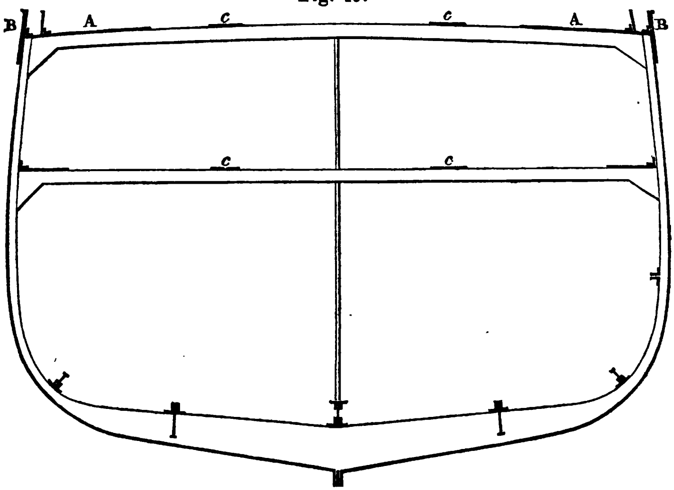
struction, 235 feet 6 inches long, and 35 feet beam, and 22 feet 9 inches depth of hold, and of a burthen of 1500 tons, we find a still better disposition of the material as respects the strength and durability of the ship.

Taking the area of the above vessel, we have as under:

		Square inches.
A A	$7' 6'' \times \frac{5}{8} \times 2$	112·5
B B	$2' 9'' \times \frac{13}{16} \times 2$	107·2
c c	$2' 9'' \times \frac{5}{8} \times 2$	30·0
c c	$2' 0'' \times \frac{11}{16}$	16·5
Side-plates, taken at		80·0
Deck-planking, say		85·8
Total area		432·0

which, by formula, assuming the bottom section to be in excess of the top, would give 4600 tons as the distributed

Fig. 49.



breaking weight for a smaller vessel. This is, however, still short of the required proportion, and admits of further improvement, as we shall presently show.

Having now directed attention to existing defects in the construction of iron vessels, I may venture to proceed

to the more important consideration of their removal, by passing from a system of apparent guesswork to a careful adherence to sound principles in design, like those established by direct experiment for other constructions governed by the same laws and subject to the same strains. If I am correct in treating iron vessels in the light of simple girders, I shall be able to show a better disposition of material, calculated to remedy present defects, and greatly increase the strength of vessels, without any great increase of cost, to resist transverse strains. If I were proceeding upon theoretical considerations, the results I have stated might be doubted; but we have a sufficient number of experiments upon hollow wrought-iron girders to calculate the strength and resisting powers of ships to transverse strain, with a near approximation to accuracy in the results.

Let us, therefore, again take the case of a vessel 306 feet long, 41 feet 6 inches beam, and 26 feet 6 inches deep, built according to Lloyd's rules as an A1 vessel of the highest class, for twelve years, from dimensions given in Table G. In such a vessel we have the best known construction, according to the highest authority, and although I do not wish to find fault, or in any way question the regulations of Lloyd's, which appear to have been drawn up with great care, yet I am of opinion that they may be greatly improved upon by the following alterations. Let us suppose the vessel to have a displacement of 5600 tons, and to be constructed with a midship-section exactly similar to what is required in the regulations of Lloyd's. In this section (shown in fig. 48), not only is the deck section defective in its resistance to a tensile or compressive strain, when compared with the bottom, but following up these rules, as laid down for the guidance of builders, two very important points seem to require revision, namely, that they make the strength of materials in vessels to be in

proportion to their tonnage, without reference to their length, and also that they require the plating, stringers, and frames at the ends of the vessel to be about the same weight and strength as at midships. Now it is at the latter part where the strength is required, as in every case the strain is greatest there, and gradually diminishes towards the stem and stern. In fact, the section of the plates and stringers ought to be double at midships, both at the deck and the bottom of a well proportioned ship.

To illustrate these facts, it will be necessary to estimate the strength of a vessel constructed according to the latest regulations of Lloyd's, for the highest class, A1 vessels, and then to point out the distribution of material which will secure perfect uniformity of strength.

Taking the length at 306 feet, beam 41 feet 6 inches, depth 26 feet 6 inches, we have the sectional areas:

	Square inches.
For the keel	42·0
Floor or bottom plates	31·5
Keelson	13·7
Angle-iron	20·0
Bottom-plates	498·0
Two stringers and angle iron	66·0
Two " "	18·0
Total area	689·2

Again, if we take the sectional area of the deck and six feet down the sides (which is a fair average of its powers of resistance to tension and compression), and allowing 130 square inches of iron as an equivalent for timber-stringers, deck-planking, &c., the area will be as under:

	Square inches.
Side-plates	144
Two stringers and angle-iron	68
Two stringers on lower deck, say	25
Timber stringers and planking	130
Two midship stringers	28
Total area	395

Here it is evident that there is a great want of proportion between the top and bottom of the ship, and in order to attain the maximum point of strength, we must increase the area of the top, retaining the bottom as hitherto constructed.

Let us assume the displacement of such a vessel to be 5600 tons; then, in order that she may be capable of sustaining half that weight suspended from her centre, or 5600 tons equally distributed inclusive of her own weight, she would require a midship-section of at least,

	Square inches.
For the bottom	535
For the top	535
For the intermediate space	130
Total area	1200

Giving by formula,

$$W = \frac{26\cdot5 \times 535 \times 60}{306} = 2780 \text{ tons},$$

the breaking-load in the centre.

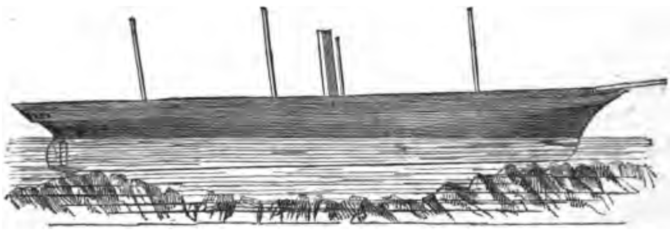
Now, in order to be secure against the vessel's breaking in two when placed in a position such as already described, we must give her a still larger margin of strength, and, in fact, make the deck as strong as the bottom in the section of Lloyd's, and we should then have by the same formula,

$$W = \frac{690 \times 60 \times 26\cdot5}{306} = 3585 \text{ tons},$$

or 7170 tons equally distributed throughout the ship. In the present state of our knowledge, it would appear that we are greatly deficient in the application of those laws which determine the strength of ships and other similar constructions; and as I have laboured for the last thirty years to determine these laws experimentally, I may probably be excused if I now seek to establish sounder principles of construction in this all-important branch of engineering — the increased security of our mercantile marine.

In our present A1 iron vessels, it is evident, according to Lloyd's regulations, that we have only 400 inches of material at the deck to balance 690 inches at the keel, and that if suspended on rocks, in the position already discussed, the ship would inevitably be destroyed with a less weight than she is actually accustomed to carry. In this Lecture I am advocating a principle calculated to provide against such a contingency, viz. that vessels of this description should be constructed with equal sections at the deck and keel, say each about 690 square inches. They would then be equally strong, whether in the position shown in fig. 47, or whether suspended on rocks at each end, in the position shown in fig. 50, with a compressive

Fig. 50.

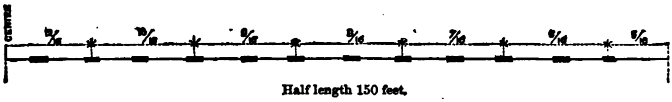


strain along the top, and a tensile strain along the keel. In either position there would be a surplus strength of 500 tons to spare as a margin against every contingency, or by whatever forces she might be assailed. Generally, I have contended for equal sections at the top and bottom; but cases may arise where stronger bottoms are necessary, as in screw colliers, which take the ground, but in other cases, the nearer the deck and bottom approach each other in sectional area the better.

It may be said that vessels constructed upon this principle would be greatly increased in original cost. To some extent, no doubt, this is true; but the material accu-

mulated towards the middle should be progressively reduced towards the stem and stern. Thick plates and large masses of iron are not required at the extremities, if uniformity of strength is to be attained. It is an utter waste of material to introduce it where it is not wanted, and, moreover, where it does not add to the security and stability of the ship. In fact, I would earnestly urge upon the attention of builders, that more care should be exercised in proportioning different parts to the strain they have to bear. I do not mean that the frames and sheathing-plates should be much reduced in size or thickness, but the longitudinal stringers and side-plates may be reduced in thickness to advantage. For example, if we take the deck-stringers and longitudinal stringers, which I recommend in order to give increased security, they should be proportioned as shown in fig. 51. These numbers

Fig. 51.

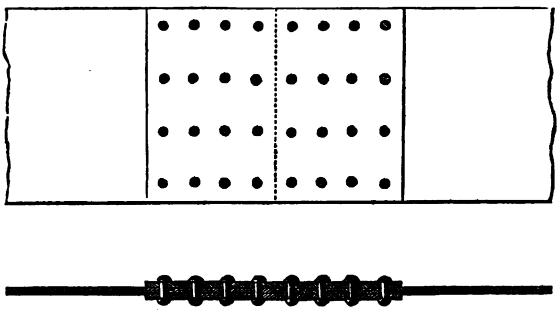


approximate to the true proportions for equal strengths; and the only deviation from these ratios should be in some parts of the exterior sheathing (probably at the bows, should the vessel come in contact with floating ice), bulkheads, frames, &c. In this way a great deal of material would be saved which does not add to the strength of the vessel.

Another feature in the construction of iron vessels is the method of forming the riveted joints. I am perfectly cognisant of the custom of double riveting, which is sufficiently strong in the longitudinal, but comparatively weak in the transverse, joints. These latter ought to have long covering plates, and should be chain riveted, as shown in fig. 52. If the joints were made on this principle, it

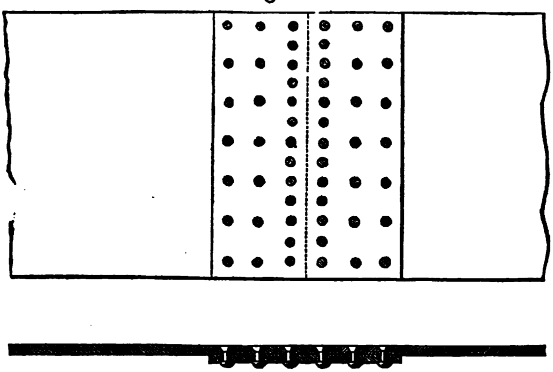
would add twenty per cent. to the transverse strength of the ship,—an important desideratum, and one which would be attained at the expense of a few more rivets and a small increase in the length of the covering plates. The secu-

Fig. 52.



rity of the ship should not be jeopardised for such a consideration; and it is to be hoped that vessels will not in

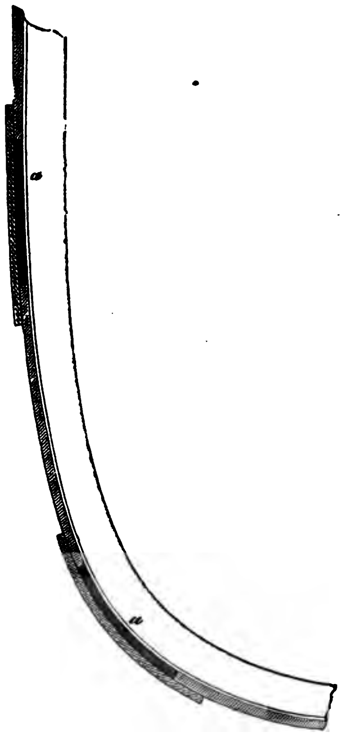
Fig. 53.



future be built at a loss of one-third of the longitudinal tenacity as at present, but that the most perfect mode of uniting the plates will be adopted in every part of the

construction. If the principle of chain riveting were adopted, we might employ the constant 80, instead of 60, in the formula for calculating the strength, and the weight and sectional area of the plates might then be reduced. This is a consideration of much importance, as the frames, or ribs, might be made two feet six inches apart to admit the necessary covering plates, and secure a better system of transverse joints, as shown in figs. 52 and 53. Below water, where a water-tight joint is the first requisite, the rivets must be placed nearer together at the joint; but we may still compensate for the loss of strength caused by the closeness of the rivets, by using a covering plate thicker than the plate, and countersinking the rivets on the outside, as shown in fig. 53. It is true that builders are not allowed, by Lloyd's rules, to place the frames more than eighteen inches apart, which only permits double riveting; but Mr. Vernon, whom I consulted on these points, and to whom I am indebted for many useful suggestions, informed me that, even with frames at this distance, each alternate tier of plates might be so riveted; the plates being arranged outside and inside, as shown in fig. 54,

Fig. 54.



wider covering plates might be introduced, as shown at *a a*, under the angle iron of the frames, and thus the outside plates chain riveted. This would be a great improvement, and add considerably to the strength of the ship. As respects the diameter of the rivets and their distances apart, the following table, deduced from experiment, and employed by myself and and others in extensive practice, may be relied upon.

Table exhibiting the best proportions for riveted joints.

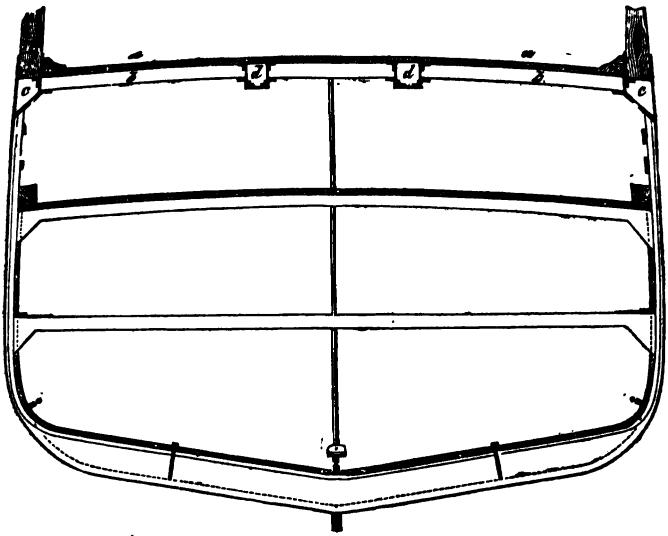
Thickness of plates in inches.	Diameter of rivets in inches.	Length of rivets from the head in inches.	Distance of rivets from centre to centre in inches.	Quantity of lap in single joints in inches.	Quantity of lap in double-riveted joints in inches.
·19 = $\frac{3}{16}$	·38	·88	1·25 } 6	1·25	
·25 = $\frac{4}{16}$	·50	1·13	1·50	1·50 } 6	
·31 = $\frac{5}{16}$	·63 } 2	1·38	1·63 } 5	1·88	Add two-thirds of the depth of the single lap.
·38 = $\frac{6}{16}$	·75	1·63 } 4·5	1·75	2·00 5·5	
·50 = $\frac{8}{16}$	·81	2·25	2·00	2·25	
·63 = $\frac{10}{16}$	·94 } 1·5	2·75	2·50 } 4	2·75 } 4·5	
·75 = $\frac{12}{16}$	1·13	3·25	3·00	3·25	

I now venture to direct attention to the plan which I propose should be adopted for securing the most effective distribution of the material which is to be added to the upper part of the ship. Iron vessels are ordinarily constructed with ribs or frames, placed from fifteen to eighteen inches apart. They are about two feet deep at the keel, and taper to the width of the angle-iron round the bilge on each side, at *a*, fig. 48. From that point to the top of the deck, the angle-iron is in some cases considered of sufficient strength for the reception of the sheathing-plates. On the top side of the ribs a lighter description of angle-iron is riveted, and to this the flooring, whether of wood or iron, is attached. This plan of construction is not objectionable, provided two more longitudinal stringers,

on each side of the keel, are made to run from one end of the ship to the other, and in large ships chain riveted, as previously recommended, which will greatly enhance the value of the ship. If this were done so as to give the required midship-section necessary for the security of the vessel, it would prove highly advantageous.

The *Great Eastern*, which is probably the strongest vessel in proportion to her size ever built, is constructed on this principle; and the designer, the late Mr. Brunel, was too sagacious an engineer to lose sight of the cellular system, developed first in the Britannia Bridge, to neglect its application to the deck as well as the hull of the monster ship.

Fig. 55.



The result of this application, with the longitudinal bulkheads, constitutes the enormous strength of this

magnificent vessel, proving the importance of the cellular system for vessels of large tonnage. It combines lightness with strength, and the double sheathing gives immense rigidity to the construction; in fact, the *Great Eastern* is a double ship up to the water-line. With smaller vessels, however, this system is not applicable; but a modification of it, as shown in fig. 55, may be safely adopted with advantage to both builder and owner. The exchange from the old system to the one I am urging will not call for any great sacrifice; the change I propose is a new and more scientific distribution of the material, and not any great increase of sectional area, and consequently of weight throughout the construction.

In the formation of the deck, it is essential, for public security, that a new principle of construction should be immediately adopted, and that the cross-beams forming the upper deck should be covered with iron stringer-plates, thickest towards the middle of the vessel, and tapering from $\frac{3}{4}$ to $\frac{5}{16}$ inch thick as they approach the stem and stern. The sectional area thus obtained, however, is short of what would be required for a vessel of the magnitude we have been considering. To secure a proportionate resisting power in the deck, we shall require the arrangement shown in fig. 55, giving an area of 750 square inches, exclusive of the hatchways, which I have estimated at 8 feet wide. This sectional area would be distributed as follows: —

Section of Longitudinal Cells, d d.

	Square inches.
2 plates, $25\frac{1}{2}'' \times \frac{3}{4}''$	38·0
6 plates, $18'' \times \frac{3}{4}''$	81·0
8 angle-irons, $3'' \times 3'' \times \frac{5}{8}''$	26·8

Section of Corner Cells, c c.

	Square inches.
6 angle-irons, 4″ × 4″ × ⅝″	27·6
2 „ 6½″ × 5½″ × ⅝″	15·0
2 plates, 31″ × ⅞″	54·0
2 „ 48″ × ⅞″	84·0
2 „ 33″ × ⅞″	57·7
2 „ 72″ × 1″	144·0
Other Plates.	
4 stringers, 24″ × ⅞″	84·0
2 stringers on lower deck	25·0
Deck-timbers, say	120·0
Total area of top	757·1

Section of Bottom.

1 keel, 12″ × 3½″	42·0
2 plates, 31″ × 1$\frac{1}{16}$″	66·0
2 lengths, 246″ × 1″	492·0
12 angle-irons, 6½″ × 5½″ × ⅝″	90·0
2 bulb-irons, 10½″ × ¾″	18·0
Keelson, 18″ × ⅞″	15·75
2 plates, 25″ × ¾″	37·5
Total area of bottom	761·25

Thus we should have in the hull and deck a maximum area of security; and the vessel, so far as regards her ultimate strength, would be superior to any tests to which she might be subjected at sea or on shore. Under the most trying circumstances she would not incur the risk of breaking, and the passengers and cargo would in all probability be secure.

In these recommendations we have not desired to teach the experienced shipbuilder the details of his business; all we contend for is greater security for life and property, obtained by adherence to sound principles of construction of well-ascertained truth. In furtherance of these objects, I would venture to suggest the following improvements and additions to the midship-section of iron vessels, viz. the introduction of two cellular rectangular stringers, one on each side of the hatchways,

and two triangular stringers, one on each side of the vessel, as shown in fig. 55. *a a* is the wooden deck, under which is a platform of $\frac{3}{4}$-inch plates, riveted to the light beams *b b*, which rest on the two triangular cells *c c*, to which they are riveted, as also to the rectangular cells *d d*, which run the whole length of the ship, and rest on the water-tight bulkheads, which divide the ship into eight separate compartments. These cells should be chain-riveted, and by the same means to be attached to the angle-iron of the bulkheads on which they are supported. These will diminish the span of the cells and lighten the deck-beams, which will not exceeed 15 feet in length from the cells *d d* to the side of the ship. It will not be necessary to go farther into detail, as the cross-beams and gusset-stays to the lower deck are of much less importance than the corresponding parts in the deck we have considered.

As respects the quality of the iron used for ship-building, the greatest care should be observed in the selection. Twenty to thirty shillings a ton will make all the difference between good plates and worthless ones, and no plates ought to be used which will not stand an average tensile strain of 20 tons per square inch. The better qualities of plates vary from 20 to 25 tons per square inch; but well-wrought plates, free from dross, and equal to an average test of 20 tons per square inch, will give to the vessel, if well constructed, adequate durability and strength.

It is from this material (iron) that we derive the instruments of our civilisation; our progress in useful art depends upon our knowledge of its application; ships of 400 to 700 feet in length, and bridges of equal span, could never have been attempted in its absence; in its varied forms and conditions, it supports our wonderful industry, and is the soul of our commerce. Viewing it in

this light, how important is the development of every new law and every new application which tends to secure its economical employment! and looking at our continued progress in our knowledge of its properties, and its conversion from the crude ore to its final condition in its various applications, we may say that the iron age of the world has come, nourishing a never-failing and widely-extending industry,—an industry which has raised this highly-favoured country to the position of the leader in practical science, and the pioneer of progress.

Having thus pointed out the defects and the remedies to be applied for giving increased security to iron ships, it simply remains for me to urge upon the merchants and builders in this great community the absolute necessity of adhering to the fixed and determined laws of physical truth which I have endeavoured, however imperfectly, to inculcate; but which, if carefully followed, will greatly extend our iron constructions, and render the iron ship of British manufacture triumphant on every sea.

LECTURE VI.

ON THE CONSTRUCTION OF IRON VESSELS EXCEEDING THREE HUNDRED FEET IN LENGTH.

In the previous Lecture I endeavoured to inculcate principles on which iron ships ought to be built in order to secure perfect safety, and to give to the public increased confidence in the stability of these constructions. In pointing out how these desiderata may be obtained, I confined my attention to vessels varying from 500 to 1500 tons burden, and not exceeding 300 feet in length and 41 feet 6 inches beam. In these constructions I attempted to prove that the present system was defective, and that in certain positions a vessel built upon this principle must of necessity break up and go to pieces. These views were not founded upon theoretical speculations, but upon experimental facts, and to which I considered it my duty to direct public attention.

It cannot be denied that the most disastrous effects have followed from these defects; and it appears imperative, for the sake of life and property, that a new and more perfect system of construction should be adopted, founded on definite laws by which the resisting powers of materials in different forms and conditions are governed. As respects iron nearly the whole of these laws are known, and we are at no loss to discover its ultimate powers of resistance in whatever positions it is placed, or to proportion its

dimensions to meet with safety the forces to which it is subjected. Possessing this knowledge, and having it in our power to apply it, why should we neglect its application in structures of such vast importance as those in which our lives and fortunes are so often embarked? The surveyors of Lloyds, most excellent, well-meaning, gentlemanly men as they are, may say what they please, but I have no hesitation in stating that their regulations are very defective and require immediate revision, and such a revision in my opinion should be based upon principles of exact science, and calculated to secure a maximum strength in the iron ship. I do not wish to find fault, nor do I assert that the alterations I have to propose are in every sense the best calculated to produce a maximum effect; on the contrary, they may require correction in practical details; but this I believe, that the present build of ships is decidedly imperfect, and admits of great improvement both as regards security and economy in the use of the material of which they are composed.

The cellular system has been objected to on the ground of the inconvenience of longitudinal stringers along the deck on each side of the hatchways, and their liability to oxidation. Now, so far as regards the deck these objections have in reality no weight, for the proposed cellular stringers need not exceed fifteen inches square, or eighteen inches wide by fifteen deep; and these, with the cells which form part of the bulwarks, will afford all that is wanted to give the required stability to that part, forming, if properly put together, perfectly rigid horizontal columns to resist the force of compression on the one hand, and tension on the other. Again, as regards oxidation, none can occur to any injurious extent so long as these cellular stringers are below deck and are riveted water-tight, which may be done with perfect safety and without diminution of their strength. From these remarks, and from

previous statements it will be seen that the excess of material is not required in the vicinity of the neutral axis, where the strain is least, but at the extreme top and bottom, where the strains are most severe when the vessel is pitching in a heavy sea.

It is a universal law of construction that the resistance provided for should be proportional to the assailant force in each part, and in order to effect security it should always be greatly in excess. In building a ship, as in other similar structures, the first thing is to ascertain the points of greatest strain, and to provide at those parts the greatest power of resistance; but to build a ship with equal thicknesses of plates throughout, or any other vessel liable to be ruptured by forces that act with double the intensity in some parts that they do in others, is not only a great waste of valuable material, but is absolutely injurious, in so far as it adds by increased weight to the destructive element that tends to break up the vessel. This being the case, how essentially necessary is it that the strengths should be carefully proportioned to the strains, and the material arranged in such a form as to offer a harmonious resistance to the forces thus acting upon it.

To effect this distribution, the object of the previous investigation, and keeping in view the same principles I there ventured to advocate, I now come to a larger class of vessels, which involve at the present time considerations of vast importance to the owners and builders and others interested in the extension of commerce. To these vessels I would now venture to apply the same principles, so as, in my opinion, to secure the necessary strength under the varied forms and circumstances to which they are subjected.

We do not know what changes are in store for us as a result of the performance of the *Great Eastern;* that vessel has not yet been fully tried, and it would be premature to anticipate results; as it is, we can only assume that she

will prove commercially successful, and although probably not to the extent expected by her more sanguine advocates, yet that she may possess qualities favourable to a considerable increase in the dimensions of our vessels both in relation to their capacity for cargo, speed, and other good properties. If we assume this as the result of the forthcoming performances of the *Great Eastern*, we may take as the basis of our inquiry a vessel of 500 feet length between the perpendiculars, and 68 feet beam. The question for consideration then is, on what principle should she be built for the purpose of attaining the greatest security with the least material? To answer this inquiry we may consider;—

1st. The general principle of construction.

2nd. The frames and ribs, and their distribution as affecting the transverse strength.

3rd. The plating or sheathing, including stringers, cells, &c., as affecting the longitudinal resistance to fracture.

4th. The decks, bulkheads, and internal fittings.

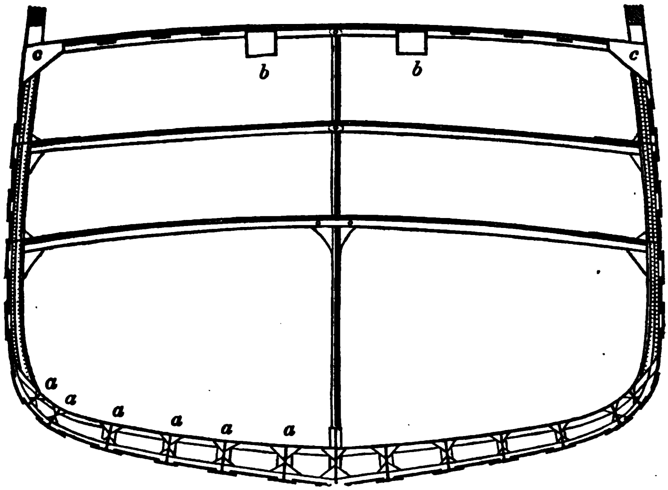
5th. The bows and stern in their resistance to concussion.

6th. The resisting powers, durability, and economy of the ship taken *en masse.*

In our attempts to apply sound principles in construction, we have two things to determine:—first, the properties of the material we have to deal with, and second, the forms and conditions in which it should be applied. In regard to the former, it is essential to sound construction that we should have good material, and on this point it will be requisite to offer a few suggestions. To those acquainted with the iron trade, it is well known that we have five or six different sorts of plate and bar iron, namely, cinder plates, common plates, best plates, double wrought plates, and the superlatively good best-best plates. The same varieties may be had in bars, and it requires no

small degree of skill and penetration to determine from appearance what is good and what is bad. One thing is however evident, that no description of plates or angle iron should be employed in shipbuilding that would not stand a test of 20 to 24 tons tensile strain per square inch. That these plates should be made from good puddled bars, piled and rolled at the proper heat, is also essential to durability and security in naval construction; and the

Fig. 56.



additional cost of 20*s.* per ton should not be an object when compared with the superior quality of the iron employed. In fact, it is a mistaken economy to suppose that a reduced rate per ton in the first cost of an iron ship is an advantage. On the contrary, it involves in reality a serious loss; the inferior material can never be depended upon, and the risk incurred in consequence is too great to lend to its employment any countenance or support. On the other hand, when a better quality of iron is used, less weight is

required, and the builder executes his work with greater exactitude and with less risk of injury to the material.

Assuming that the material is unexceptional as to quality, we have next to consider the principle on which large vessels, 500 feet in length, should be constructed for the purpose of obtaining the maximum of strength with the least material. In this case it will be necessary to depart from the ordinary rules of construction, and instead of a closely packed series of transverse frames, it will be important to place the principal frames at distances of 4 feet apart, using the remainder of the material in the shape of longitudinal keelsons or stringers, as shown at *a a*, fig. 56.

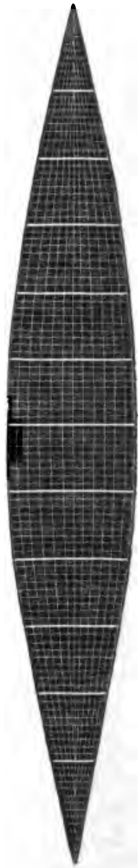


Fig. 57.

Framing the hull of the ship in this form gives greatly increased stability, and in a vessel of this magnitude the whole of the material in her hull will be arranged in parallelograms, measuring at midships 6 feet by 4 feet, and narrowing as they approach the stem and stern until the lines of the vessel bring them in contact, at which point two cells would run into one till the extreme points were reached at each end. If we remove the iron sheeting, the bottom of the ship will present a large honeycombed surface, as in fig. 57. Now of all forms this is the strongest, and a large vessel constructed in this way would have immense rigidity, and form one continued line of walls or girders, greatly in favour of the material, and adding much to the strength of the ship.

Besides, in the above form the plates forming the keelsons and frames may be much reduced in thickness, and two-thirds of the transverse frames being dispensed with, we can afford to increase the number of longitudinal keelsons without increasing the weight of the material in the ship.

For comparison, let us estimate the strength upon this construction and that on the plan of frames 18 inches apart, with only three longitudinal keelsons in the bottom. In the proposed improvement there are 13 longitudinal keelsons, and these, with the outer and inner sheathing at the bottom, cellular deck, &c. would probably give a displacement of 4500 tons.

Area of Bottom.

		Ft.	Ft. In.		Sq. ins.
1.	Centre keelson	500 ×	6 × $\frac{3}{4}$	and angle iron	72
2.	Keelsons	,,	4 × $\frac{5}{8}$	,,	90
4.	,,	,,	$3\frac{1}{2}$ × $\frac{1}{2}$	,,	132
2.	,,	,,	3 × $\frac{1}{2}$	,,	60
2.	,,	,,	$2\frac{1}{2}$ × $\frac{1}{2}$	,,	54
2.	,,	,,	2 × $\frac{1}{2}$	,,	48
			Total keelson area		456
80 feet of sheathing plates averaging $\frac{3}{4}$ in. thick					720
60 feet interior sheathing averaging $\frac{3}{8}$ in.					270
			Total area of bottom		1446

We suppose the upper part of the ship along the deck to be formed on the same principle as advocated for ships of 300 feet length in the previous lecture, with two cells near the centre, *b b*, and with two square and two triangular longitudinal cells, *c c*, at the side, extending the whole length of the ship, as shown in the section, fig. 56. We should then have with the stringer plates, deck planking, &c., the following sectional area: —

Area of the Top.

	Sq. ins.
2 middle cells 20 in. × 20 in. × $\frac{3}{4}$ in.	120
2 side cells 30 in. × 18 in. × $\frac{3}{4}$ in.	142
2 triangular side cells 36 in. × 36 in. × $\frac{3}{4}$ in. . .	162
Angle iron to the above	138
16 feet of plates on sides = 192 in. × $\frac{3}{4}$ in. . . .	144
Deck stringers 360 in. × 1 in.	360
Deck planking, say	300
Total area of top . . .	1366

This gives an excess of 140 sq. ins. in favour of the bottom as a compensation for extra wear and tear on that part.

The strength of a vessel built in this form with the above sectional areas, and properly constructed to resist a lateral strain, may be found as before by applying the formula $W = \frac{adc}{l}$. With the constant 60 as before, and taking the smaller or deck area,—

$$a = 1366 \qquad c = 60$$
$$d = 40 \qquad l = 500$$
$$W = \frac{1366 \times 40 \times 60}{500} = 6556{\cdot}8 \text{ tons}$$

the breaking weight at the centre, or 13,113·6 tons with the load distributed. Again, comparing this with the weight of the ship and cargo, and taking her loaded draught at 24 feet, we have a displacement of about 9800 tons, which it will be observed leaves a margin of strength of 3313 tons, sufficient for all practical purposes as regards the durability and safety of the ship.

We could multiply these calculations to any extent, but I only wish to point out for the guidance of engineers what we consider the best and most effective principle of construction to ensure a powerful resistance to strain, and

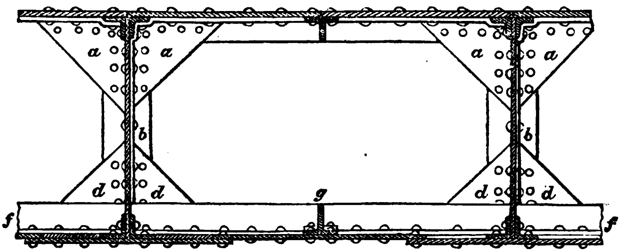
a distribution of material capable of withstanding the shocks of a rolling sea, or any other trials to which in extreme cases the vessel might be exposed.

Water-tight bulkheads are of great importance in the class of vessels we are now considering. These not only bind the sides of the ships together from the keel to the deck, but they give rigidity and strength to the whole structure, and there is no part more deserving of attention in large ships than these bulkheads. In a ship of 500 feet length and 68 feet beam, it might be desirable to divide her into two parts by a longitudinal bulkhead up to the middle deck. That would, however, be inconvenient in many cases in both sailing vessels and steamers. In fact, in the latter it would be inadmissible on account of her machinery; we must therefore deal with the construction under those conditions required by the service for which she is intended. This does not, however, affect the general principle that bulkheads made perfectly water-tight and stiffened with angle and T-iron should form component parts of the structure, and require great attention both as to the number of compartments and the position in which they are placed.

It now remains for consideration in detail whether the principle of longitudinal keelsons, with corresponding plate and cellular stringers, is or is not superior to the ordinary construction with transverse frames. In vessels of such immense tonnage, it would appear from the formula applied to hollow girders that a great increase of transverse strength may be gained, as in the case of smaller vessels, previously considered. In a vessel floating on water the force of external pressure at a depth of 24 feet is about 1572 lbs. per square foot, or 11 lbs. per square inch, and this distributed over the surface of one of the cells, 6 feet by 4 feet, amounts to 17 tons nearly, or is equivalent to a force of 8½ tons at the centre of the cell at midships. Now

this would be too great a pressure for a ¾-inch plate, and would cause a bulging inwards, were it not for the counter-poising pressure on the adjoining cells, which has a tendency to neutralise the bulging tendency by straining the metal uniformly over the keelsons and transverse ribs. In order, however, to increase the rigidity of these parts, it will probably be necessary to run down the middle of each cell bars of T-iron 6 ins. by 5 ins. as shown at *g*, fig. 58, in

Fig 58.

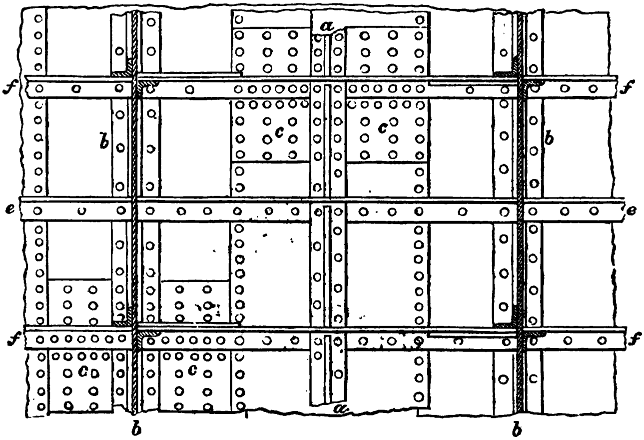


the line of the keelsons *b b*, composed of angle irons and vertical plates riveted to the sheathing plates 3 feet wide and 12 feet long. On this principle the T-iron would also rest upon the longitudinal plates, and the transverse joints would be covered by the plates, shown at *c c*, fig. 59, placed under the frames and chain-riveted. The covering plate in this case being thicker than the sheathing plates, in order to compensate for an increased number of perforations for rivets along the line of the joint.

It has been stated that it would be necessary to have an increased number of transverse frames in order to bring the lines of the vessel into shape; should this prove correct, another light rib may be used, shown at *e e*, in the plan, fig. 59, riveted to the sheathing on the same principle as the other ribs *f f f f*, which are four feet asunder. These

practical details, however, we may leave to the judgment of the builder, as not essential to the stability of the ship. In this way the resistance of the cells to bulging would be more than doubled, and the whole of the cellular construction rendered secure under every form and condition of strain. The preceding sketch (fig. 58) represents the sectional form of the cells, each of which may be stiffened by gussets, *a a* and *d d*, riveted to the angle iron of the keelsons and transverse frames. Fig. 59 shows in plan the keelsons, *b b*, ribs, *f f*, additional rib, *e e*, T-iron along the bottom, *a a*, and covering plates, *c c*, chain-riveted. On this plan the cells would be open from one bulkhead to the other, and with proper water-tight manholes between each bulkhead might, if necessary, be used for stowage or for the insertion of tanks in which fresh water might be kept ready for use.

Fig. 59.



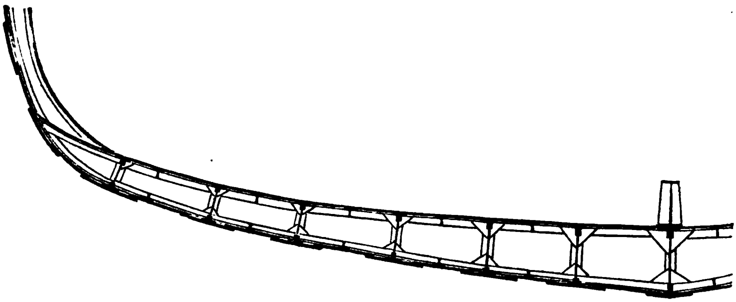
On the above construction the sheathing plates would be lap-jointed, using the keelson angle irons and the intermediate T-irons as stiffeners for the cells, as shown in fig.

60, which represents one half of the cellular system at the bottom of a vessel from the keel to the turn of the bilge.

Enlarged covering plates, chain-riveted, for the transverse joints, are of great importance both in regard to the lateral and longitudinal strength of the ship. The resistance to tension would be one-sixth greater than with the ordinary construction, and thus the security of the ship would be greatly increased.

As regards the upper and intermediate decks, there would be no change except the introduction of two cells,

Fig. 60.



one on each side of the hatchways, and four other cells, two on each side of the ship, as shown in fig. 56. In the sectional area of the upper deck it will be observed that in the previous calculation we allowed about $\frac{1}{6}$th as the value of the deck planking in resisting a compressive or tensile strain, and that we made a further allowance of material to the bottom to compensate for the wear and tear of those parts. Hence, the sectional area of iron in the upper deck will be to that in the bottom in the ratio of 4 to 6. These proportions have been assumed, but they are in accordance with experimental researches, or at least so far as we have results bearing on this question; and it

only requires an extension of such experimental investigations to prove how far these proportions approximate to the correct ratio for resisting the strains at those parts respectively.

A series of well-conducted experiments of this kind are much wanted, and a government grant of 1000*l.*, with a similar grant from Lloyds and from the shipowners' fund, would set the question at rest, and establish in shipbuilding, as in other constructions, true principles, the correct expression of physical laws. It is with the object of aiding in the attainment of this that I have ventured to make these suggestions. The subject is one of deep importance to the community, one on which we are very deficient in knowledge, and one which will reward investigation, and that with great benefit to the public and to mechanical science, and without injury to existing interests.

Impressed with the conviction that we are still labouring under difficulties from a want of knowledge of the true principles of naval construction, we are encouraged from other movements in looking forward to the time when these difficulties will be removed, and when greater economy in the distribution of the material will be accomplished, from the reduction of the whole system of shipbuilding to the exact laws of science.

In the discussion of this question I have not ventured to inquire into the applicability of the cellular construction to ships of war, and my reason for the omission has been that the effect of shot upon iron ships has yet to be decided upon. I am aware that the Admiralty some years since came to a conclusion adverse to the use of iron, which I am not now prepared to call in question. But the improved condition of our iron constructions, and the increased tenacity of the material, taken in connection with our improved system of gunnery, may afford reasons for

altering that decision, and lead to results favourable to the use of iron as a material for building vessels of war.

With the Whitworth rifled gun, for example, with an oblong flat-ended missile, iron is penetrated by a process that drills or cuts out the core without splintering or tearing up the surrounding surface, and looking forward to still further improvements, the iron ship may be increased with safety under the influence of a more destructive arm than has heretofore been used. Be this as it may, the same principles of construction will apply to the navy as to the vessels of the merchant service; and till it it has been more conclusively proved that iron is inapplicable to the construction of ships for the purposes of war, we may reasonably conclude that this material may ultimately become the best safeguard of Her Majesty's dominions at home and abroad.

[Since the above was written I have deemed it necessary to insert in the Appendix two letters addressed to the editor of the "Times," bearing directly on the defective construction of iron ships. These letters were written after the loss of the *Royal Charter* by a near and dear relative, and are so much to the purpose, that I should consider myself wanting in duty if I omitted statements of such importance to the public. I have also given a quotation from a recent lecture of Mr. Grantham's, in which he shows with great clearness some of the causes of weakness in our present construction, having arrived, independently, at nearly the same conclusions as myself on the necessity for a large increase of transverse strength.]

LECTURE VII.

ON WROUGHT IRON TUBULAR CRANES.

THESE structures are identical in principle with the tubular bridges over the Conway and Menai Straits, and present additional examples of the advantages which may yet be derived from a judicious combination of wrought iron plates in constructions requiring security, rigidity, and great strength.

About ten years ago the first design for a wrought iron crane was submitted to the Admiralty for their approval. It was a crane calculated to afford greater security and facility in the embarkation and disembarkation of heavy stores, and was in other respects better qualified for raising heavy weights than the cranes previously in use. The design was placed in the hands of the Surveyor of the Navy and Mr. Lloyd the Inspector of Machinery, who were so well satisfied as to the superiority of the construction that an order was given to erect six of them, in different positions along the line of quays of the new docks at Keyham and Devonport.

These cranes were all of the same size and strength, and were intended to lift weights of 12 tons to a height of 30 feet above the ground, and to sweep them round over a circle of 65 feet in diameter; so that the projection of the jib was 32 feet 6 inches from the centre of the stem, and the extreme height 30 feet above the working platform.

The cranes were composed of wrought iron plates riveted together, and so arranged as to give the back or convex side an adequate degree of strength to resist tension, and the front or concave side, which in these cranes was of the cellular construction, a corresponding power to resist compression. The form was similar to that of the prolonged vertebræ of the bird, from which the machine takes its name; it was truly the neck of the *crane*, tapering from the point of the jib, where it was 2 feet deep by 18 inches wide, to the level of the ground, where it was 5 feet deep and 3 feet 6 inches wide. From this point it again tapered to a depth of 18 feet below the surface, where it terminated in a cast-iron shoe, forming the toe on which the crane revolved.

The lower or concave side, which had to resist a force of compression, consisted of plates forming three cells, varying in width in the ratio of the strain at each part; and on the other hand the convex or top side, which has to bear the pull or tension due to the suspended weight, was formed of long plates connected together by the system of "chain-riveting," first applied in the tubular bridges in Wales. The sides were of uniform thickness throughout, the joints being covered with T-iron internally, and on the outside by strips 4½ inches wide.

The form of the jib is shown in fig. 61, with a portion of the side removed from A to the foot, in order to show the cast-iron cylinders built into the masonry; and the rollers which encircle the body of the crane and support the jib vertically, permitting, however, free motion of revolution as they roll against the large circular plate *a a*. Immediately above the rollers is a platform A, 12 feet in diameter, attached to the jib, on which the men stand to work the crane; *b* is one of the winches connected by gearing with the barrel in the interior of the crane, on

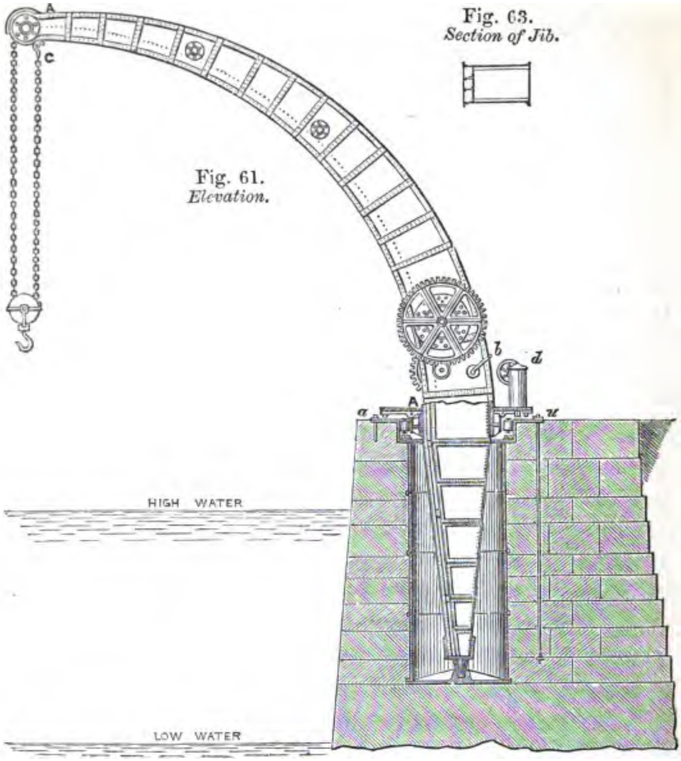


Fig. 61.
Elevation.

Fig. 63.
Section of Jib.

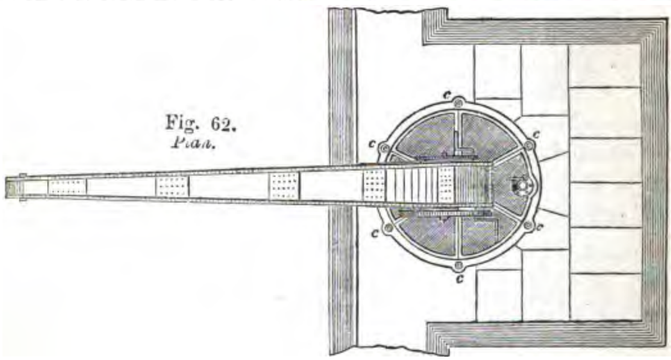


Fig. 62.
Plan.

which the chain is coiled, and *d* a wheel connected by gearing with a spur segment wheel fixed on the masonry, by which the crane may be revolved in any direction at pleasure.

Fig. 62 is a plan of the crane and platform, showing the upper flanch of the large ring *a a*, with the holding down bolts *c c c*. Fig. 63 is a section of the jib of the crane, showing the cells on the concave side of the jib.

As this was an entirely new construction, it was considered desirable to test its powers of resistance to strain, and to determine by direct experiment the law of strength which it followed. To accomplish this, each of the cranes was loaded progressively with weights up to 20 tons, the deflections being carefully recorded as the experiment proceeded.

No. 1 Crane, Nov. 8th, 1850.—With 5 tons suspended the crane was turned completely round without any alteration in the deflection. With 10 tons suspended the crane was again turned round, and in 8 minutes the deflection increased from 1·70 inch to 1·85 inch, at which it remained after sustaining the load during the whole of the night, a period of about 16 hours. The next day the experiments were resumed; and on turning the crane round with a load of 20 tons, there was no perceptible alteration in the deflection, and the permanent set after removing the load was ·64 inch. Hence the deflection was 3·33 inches for a load of 20 tons. The ultimate strength of the crane is therefore much greater than is requisite in either theory or practice; and although tested with nearly double its intended load, this was still far short of its ultimate power of resistance, which by calculation is five times greater than its nominal power.

No. 2 Crane, Oct. 8th, 1851.—With 5 tons suspended the crane was turned completely round without any

perceptible change in the deflection. With 10 tons suspended the crane was again turned round, when the deflection increased from 1·68 inch to 1·87 inch; on removing the load the permanent set was found to be ·25 inch, being the amount of loss of elasticity due to a load of 10 tons suspended from the extreme point of the jib. With 15 tons suspended the crane was turned round with an increase in the deflection of only ·06 inch. Previous to removing the final weight of 20 tons the crane was turned round, in order to test the efficiency of the movable parts, and also the break wheel, which at this trial was used for lowering the load. On removing the weights, it was ascertained that the retaining powers of the riveted joints and the elasticity of the parts in combination exhibited rather more tenacity than in the first crane that was made, as the jib when relieved from the load of 20 tons rose to within ·62 inch of its original position.

No. 3 Crane, Jan. 7th, 1852.—In this and the succeeding experiments the cranes exhibit still greater powers of resistance as regards the strength or ultimate deflection of the jib. The defects of elasticity are also diminished to an extent which clearly shows that the workmen had become more expert and probably more careful in the fitting and riveting of the parts.

In turning round the crane No. 3, the deflection remained unaltered with 5 and 15 tons load, but increased 10 inch with 10 tons load. On removing the load of 20 tons the permanent set was found to be only ·40 inch, which gives 3·16 inches as the deflection due to the load of 20 tons.

No. 4 Crane, Feb. 4th, 1852.—The results of the experiments on this crane correspond closely with those enumerated for No. 3. The same indications of strength,

elasticity, and deflection follow each other with remarkable precision. No alteration in deflection took place when the crane was turned round with loads of 5, 10, and 15 tons. The crane was turned round with the load of 20 tons, when the permanent set was found to be ·62 inch, making the deflection 2·94 inches for the load of 20 tons.

No. 5 Crane, Feb. 6th, 1852.—This crane was subjected to the same treatment with nearly the same results. In turning it round with 5, 10, and 20 tons load the deflection remained the same; with 15 tons load the deflection increased ·05 inch in turning round. On removing the load of 20 tons, the permament set was ·44 inch, giving a deflection of 3·18 inches due to the load of 20 tons.

No. 6 Crane, Feb. 14th, 1852.—In turning round with 5 tons load the deflection increased ·07 inch; but with 10, 15, and 20 tons load no change took place in turning round. On removing the load of 20 tons, the permanent set was ·50 inch, giving a deflection of 3·25 inches for the load of 20 tons.

In the above experimental tests, it is satisfactory to observe that the resisting powers of this construction are limited only by the weight of the foundations and the strength of the chains, wheels, and machinery for lifting the load. A crane of 12 tons has a stem and jib capable of supporting 60 tons, or five times the load it is intended to bear, a much greater margin than is generally allowed for constructions of this kind.

The following Tables give a summary of the results of the experiments on the twelve ton cranes at Keyham.

Table I.—*Deflections of Tubular Wrought Iron Cranes.*

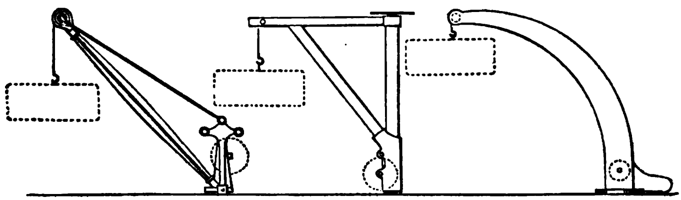
Load at end of Jib.	Deflection at the end of Jib.					
	No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.
Tons.	Ins.	Ins.	Ins.	Ins.	Ins.	Ins.
2	·32	·31	·37	·25	·27	·31
3	·50	·50				
4	·65	·62				
5	·90	·87	·87	·75	·88	·82
— turned round	·90	·87	·87	·75	·88	·89
6	1·05	1·06				
7	1·20	1·18				
8	1·35	1·37				
9	1·50	1·50				
10	1·70	1·68	1·70	1·62	1·62	1·76
— turned round	1·85	1·87	1·80	1·62	1·62	1·76
11	2·05	2·05				
12	2·22	2·19				
13	2·40	2·40				
14	2·60	2·62				
15	2·80	2·80	2·69	2·56	2·63	2·31
— turned round	2·80	2·86	2·69	2·56	2·68	2·31
16	3·00	3·00				
17	3·20	3·31				
18	3·50	3·50				
19	3·73	3·69				
20	3·97	3·92	3·56	3·56	3·62	3·75
— turned round	3·97	3·92	3·56	3·56	3·62	3·75

Table II.—*Summary of Results.*

Number of Crane.	Deflection at Point of Jib with 20 tons load.	Permanent set with 20 tons load.
	Ins.	In.
No. 1.	3·97	·64
No. 2.	3·92	·62
No. 3.	3·56	·40
No. 4.	3·56	·62
No. 5.	3·62	·44
No. 6.	3·75	·50
Average	3·73	·54

The average permanent set being deducted from the average final deflection leaves 3·19 inches as the average deflection for a load of 20 tons, which is at the rate of ·16 inch per ton. These experiments present a remarkable consistency and uniformity in the strength and elasticity of the material under strain; and it will be observed that the permanent set, varying from ·40 inch to ·64 inch, is small in amount when compared with the load and the peculiar nature of the strain to which the jib was subjected.

Fig. 64. Fig. 65. Fig. 66.



In the construction of cranes, whether of wood or iron, it has been the usual custom to place the jib in an inclined position at an angle of about 40° or 45° with the stem, as in figs. 64 and 65, so as to obtain the greatest strength; in this position the extreme point from which the load is suspended has to be stayed or held in its place by oblique or horizontal tie rods. With this arrangement it will be observed that, if the article to be raised be at all bulky, such as a large bale of merchandise or a marine boiler, it will be prevented from being elevated to the top of the crane by coming in contact with the diagonal stay or jib. Hence with ordinary cranes a considerable part of the height is practically unavailable. In the wrought iron crane, however, fig. 66, this defect is obviated, since the

curvature of the jib is sufficient to allow the article to be raised to the highest point to which the chain ascends.

The advantages peculiar to this construction of crane are its great security and the facility with which bulky and heavy bodies can be raised to the very top of the jib without the least risk of failure. It moreover exhibits, when heavily loaded, the same restorative principle of elasticity as is so strikingly exemplified in the wrought iron tubular girders. These constructions, although different in form, are nevertheless the same in principle, and undoubtedly follow the same law as regards elasticity and power to resist fracture.

Several cranes of the same power and construction have lately been erected at Keyham, Devonport, Birkenhead, and Southampton, and at St. Petersburgh, all of which have been severely tested by the suspension of weights considerably greater than they were intended to bear. Ten ton and three ton cranes have been experimented upon in a similar manner and attended with the same results; all of them exhibiting great powers of resistance, greatly increased convenience for raising the load under the curvature of the jib, and equal facility in moving the crane to any point within reach of the sweep.

Subsequently to the erection of these, the first cranes on the tubular system, a number of others followed of different dimensions, and for various purposes, all of which exhibited the same powers of resistance and other advantages. It is, however, due to the Government to state that they took the initiative in the introduction of this new system, and finding the twelve ton cranes to work to their entire satisfaction, they ordered two more for Devonport, and a colossal crane, to lift 60 tons, for Keyham. These, and many others of smaller and larger sizes, have since been erected upon the same principle, the only change in their construction of importance being the abandonment

of the cells in all but the largest, and the substitution of strong T iron ribs in their place, by which sufficient strength is secured with greater facility and economy. They have also been adapted for railway travelling cranes, and in many cases have had an engine and boiler attached to the platform, so as to work them by steam.

The colossal 60 ton crane at Keyham consists of a rectangular wrought iron tube, curved to a radius of about 46 feet, and tapering uniformly from 9 feet deep by 5 feet 6 inches wide at the level of the ground, where from the leverage of the crane the strain is the greatest, to 3 feet 6 inches deep by 2 feet wide at the point of the jib. From the level of the platform it is also tapered downwards to about 1 foot 8 inches square at 23 feet below the level of the ground, where it fits into a cast iron shoe working in a socket or step on which the crane revolves. The point of the jib is 60 feet above the level of the platform, and sweeps a circle of 53 feet radius; so that it will lift the heaviest load perpendicularly from a mean distance of 37 feet from the quay wall, and to a height of no less than 85 feet above low water mark, and land it at 69 feet from the edge of the quay.

The crane itself is built on precisely the same principle as the tubular bridge, and may indeed be considered as a curved tubular girder inverted, the top side being the front or concave side of the crane, and the bottom side forming the convex or back part of the structure. Hence it may be described as composed of back plates, side plates, and cell plates.

The back plates, which correspond with the bottom plates of a tubular girder, have to resist a strain of tension, are made as long as possible to avoid joints, and are carefully chain riveted. They are $\frac{3}{8}$ inch thick, and each half the width of the crane; and taking those on one side and beginning at the bottom of the well, the first plate is

13 feet 9 inches long; the second, which passes the point where the downward taper ends and the upward begins, is 13 feet 6 inches long; the next is 12 feet 6 inches, followed by six others, each 12 feet long, and these again terminated by a plate 15 feet long, which curves round over the pulley at the extreme point of the jib. These plates are covered externally by a long strip 8 inches broad and $\frac{3}{8}$ inch thick, extending the entire length of the crane and covering the longitudinal joint between the back plates. The cross joints are placed alternately, and at each side of the crane there is a line of angle iron connecting the back plates with the side plates. So that the sectional area of the back of the crane subjected to tension is

At the bottom	10·50 square inches.
At the platform . . .	27·75 „
At the point of the jib . . .	12·00 „

The sides of the girder are formed of plates 3 feet broad at the outer edge or back of the crane, riveted together with T iron $4 \times 2 \times \frac{3}{8}$ inches at every joint inside, and a strip outside, to give the necessary rigidity. Beginning at the toe, the first three plates are $\frac{3}{8}$ inch thick; the next three $\frac{5}{16}$ inch thick; the next five, which have to resist the horizontal thrust against the cast iron circle at the top edge of the well, $\frac{3}{8}$ inch thick; and the remainder $\frac{5}{16}$ inch thick.

The front of this crane is constructed with four cells, to resist the immense compressive strain to which that part is subjected. The two series of plates which form the front and back of the cells, are composed of plates varying from 5 feet to 7 feet 6 inches long, and $\frac{5}{16}$ inch thick. Each of these plates is riveted to the side plates by two angle irons. The space between them is divided into four cells by three vertical plates parallel to the side plates, and

eight angle irons at the corners further strengthen the structure thus formed. The reason of this arrangement is that wrought iron plates from their flexibility offer but a small resistance to compression in the direction of their thickness, as they bend or buckle with a comparatively small force. The five vertical plates, however, which form the sides of the cells, are placed in the position in which they offer a maximum resistance to compression, namely with their width or depth in the direction of the strain; and the angle irons and the plates E and F serve to keep them in position and give great rigidity to the structure. The centre plate of the cells is $\frac{5}{16}$ inch thick, and the two remaining plates each $\frac{4}{16}$ inch thick. The sectional area of the concave or front part of the crane subjected to compression is therefore

At the platform . . .	62·58 square inches.
At the point of the jib . . .	34·83 „

Attached to the back of the crane is a tail piece or box of wrought iron, containing cast iron weights acting as a counterpoise to the jib. The chain is attached to the crane by a bolt and nut at the point of the jib, and passes round four pulleys, two moveable and two fixed, in the end of the jib; it is then conducted down in the interior of the jib over three rollers to the barrel, which is also in the tube near the ground. On each side of the crane a strong cast iron frame is fixed for receiving the axles of the spur wheels and pinions. Four men, each working a winch of 18 inches radius, act by two 6 inch pinions upon a wheel 5 feet $3\frac{3}{4}$ inches diameter; this in its turn moves the spur wheel, 6 feet 8 inches diameter, by means of an 8 inch pinion, and on the axle of the former the chain barrel, 2 feet in diameter, is fixed. Hence the advantage gained by the gearing will be

$$\frac{W}{P} = \frac{18 \times 63{\cdot}75 \times 80}{6 \times 8 \times 12} = 158\,;$$

or taking the number of cogs in each wheel

$$\frac{W}{P} = \frac{18 \times 95 \times 100}{12 \times 9 \times 10} = 158 ;$$

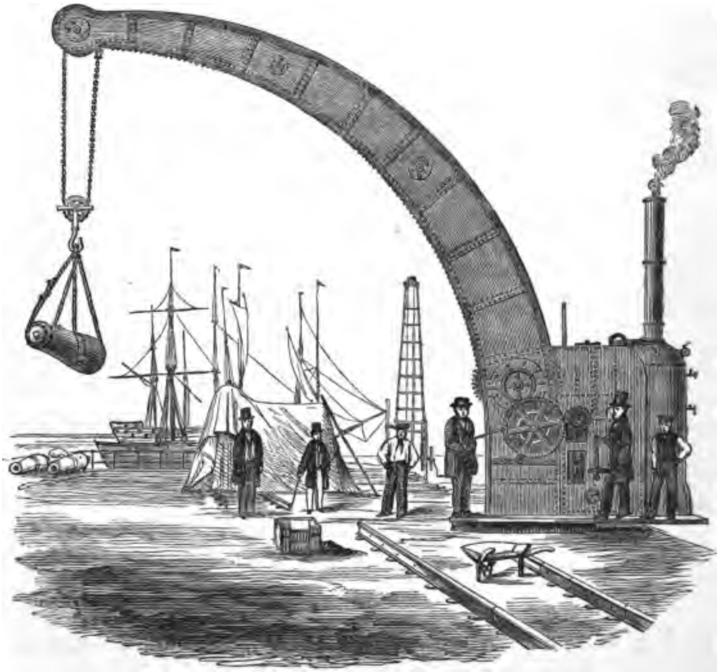
and as this result is quadrupled by the fixed and moveable pulleys, the power of the men applied to the handles is multiplied 632 times by the gearing and blocks. A break wheel, 5 feet 2 inches diameter, is fixed on the other end of the spindle of the spur wheel; and the power applied at its circumference is accordingly multiplied about 100 times by the gearing and blocks.

At the level of the ground the crane is firmly fixed in a strong cast iron frame, the outer edge of which is a circle of 11 feet 3 inches diameter; and on the edge of the well a similar ring is embedded in the masonry and secured by long holding-down bolts, leaving a space of 10 inches all round between it and the inner ring. In this space a number of strong cast iron rollers are placed, 10 inches in diameter, to prevent friction and facilitate the movement of the crane as it revolves round its axis. Upon the cast iron ring on the quay wall is fixed a circular rack, composed of cogged segments bolted together, into the teeth of which a pinion works, whereby the crane is made to revolve. This pinion is worked by a worm and wheel placed in the counterpoise box; and two men are sufficient to move round the crane with 60 tons suspended from the extreme point of the jib. In working the crane the men stand upon a cast iron platform attached to it a few inches above the level of the ground.

This crane, taking it altogether in regard to its strength, height, and the extent to which the weight raised can be swung round, is probably one of the first and most powerful in Europe. It can raise or lower boilers in and out of the holds of ships of the line; pick up the heaviest ordnance from any of the decks; and ship or unship masts

with the same or greater ease than is now done by the large shears used for that purpose in any of the dockyards. In fact a colossal crane of this description, 120 feet high, was submitted to the surveyor of the navy as a substitute for the large masting shears at Woolwich, which were worn out, but owing to some other arrangement the project was not carried into effect.

Fig. 67.



Since the erection of the 60 ton crane at Keyham, a steam engine has been fixed upon the counterpoise platform, which renders it independent of manual labour, and

gives greater facility and despatch in raising heavy weights. A crane of the same size as this has since been erected at Portsmouth dockyard, and has also an engine and boiler attached to the platform behind the crane, so that if occasion require it can be worked by steam. The engines consist of two seven inch cylinders with link motions, similar to those of a locomotive, by which they can be stopped or reversed with the greatest ease.

Fig. 68.

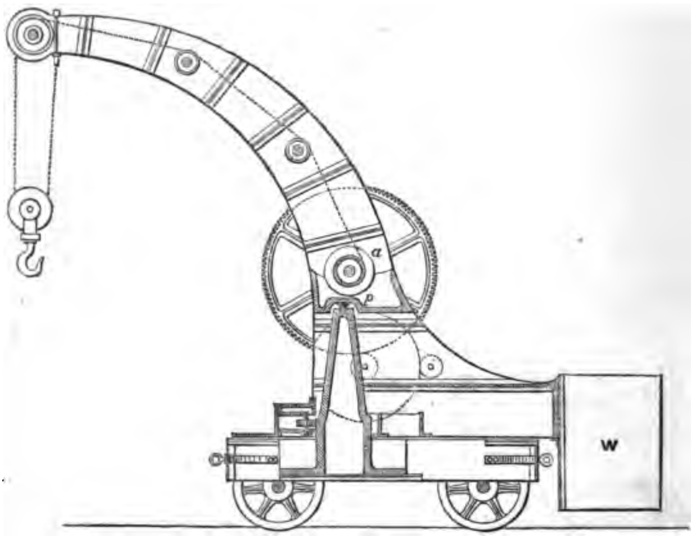


Fig. 67 is a general view of a ten ton crane on the same principle, with its engine and boiler attached. This crane sweeps a circle of 50 feet in diameter, and lifts to a height of 26 feet above the platform. The cylinders of the engine are 6 inches in diameter, to obtain a rapid elevation of the weight, and have link motions and reversing gear, as in

the larger cranes. If necessary they may be at once disconnected, and the cranes worked by hand.

The tubular principle has also been applied to railway travelling cranes, as shown in fig. 68, which is a sectional elevation of a 15 ton crane upon its truck. This crane revolves upon a steel pivot at *p*, and is balanced by a weight of about 8 or 10 tons attached behind the jib at w. In other respects it is precisely similar in construction to the stationary cranes previously described. It sweeps over a circle of 25 feet in diameter, and lifts to a height of 18 feet above the rails. The chain barrel is protected from the weather within the jib, as shown at *a*.

From the above description it will be seen that the great advantages of these constructions is their extreme lightness as compared with the weights they have to lift, and their powers of being extended to any amount of strength, height, or sweep that may be wanted. In conclusion, they are admirably adapted for the loading and discharge of cargoes from vessels in dock, and for the transfer of the load to any point within the limits of a circle described by the chain suspended from the jib.

LECTURE VIII.

ON THE PROPERTIES OF STEAM, ITS MANAGEMENT AND APPLICATION.

[Delivered before the Leeds Philosophical Society. March 1860.]

If we were to enter upon the statistics of the accidents which have arisen from the use, or rather the *abuse* of steam, we should have to present a fearful catalogue of catastrophes and loss of life. Few people are fully aware of the suffering which these accidents have entailed upon a certain class in the community, or of the immense destruction of property which has proceeded from the misdirected employment of steam.

The Great Author of Nature has supplied us with a power which properly applied changes the destinies of nations, and confers unheard of benefits upon the human race. We have it at command in every department of human effort, and in every condition of life it subserves our will through every gradation from one to a thousand horses power. It stems the tides and currents of the ocean. It ploughs, spins, weaves, and grinds our corn. It drains mines, pumps water, and carries us across the country with a celerity unknown in the past, and with a despatch and power which would have set at defiance the Genie of the Arabian Nights. It only requires a careful and judicious treatment, in preserving it from excesses of heat and cold, and confining it within bounds sufficiently strong to retain it, and a wise direction of its efforts, founded upon a clear and accurate knowledge of its properties.

When we look around us and count the number of steam engines at work in every city, town, and hamlet; when we see them traverse the rail, and depart across the ocean with unerring certainty, and consider at the same time the necessity of having all these movements under safe control, it assuredly follows that the makers of these engines and those who employ them should bring to their construction and superintendence a large degree of intelligence and a full knowledge of their principles. Unfortunately this is not always the case; we are still deficient of knowledge on many points of construction and in regard to many of the properties of steam. To supply part of that knowledge is the object of the present address, in which I hope to show some of the means by which steam boilers may be made more secure, and to correct some erroneous views which have obtained currency in regard to the properties of steam.

I. NEW PRINCIPLES IN THE CONSTRUCTION OF BOILERS.

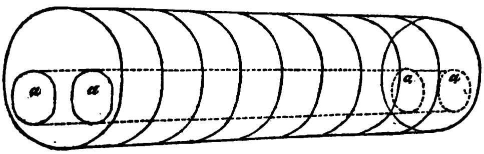
The production of steam in a vessel placed over a fire is a simple and well-known process, and one which requires no comment. The form of the vessel, commonly called the boiler, when steam is to be produced for industrial purposes, is, however, an important consideration, both as regards economy and strength. In the history of the steam engine we find an immense number of forms of boilers, most of them having served the purposes for which they were intended. At first, when high pressure steam was scarcely known, great strength was not required, and the form of the boiler was not of so great importance as at present. At that time the supply of water was regulated by a float, and the pressure in the boiler seldom exceeded 10 or 12 lbs. per square inch. At this pressure the waggon-shaped boiler and other forms with flat surfaces were not so objectionable; but when steam is employed at from five to fifteen times this pres-

sure, it becomes a question of the highest importance that the vessels to retain such an immense force should be constructed of the best material, duly proportioned in thickness, and arranged in the form of maximum strength.

In former lectures I have discussed the rules and proportions for the construction of boilers adapted for stationary engines, especially in reference to the resisting powers of the outer shell. At the time that those proportions were given we were not aware of a hidden source of weakness, which further investigation has discovered, and which we now propose to remedy by simple means, which have been suggested by an increased knowledge of the laws of construction.

It is well known that the great majority of the boilers in this country are now constructed with internal flues or

Fig. 69.



tubes traversing the whole length of the boiler, most of them being upwards of thirty feet long, and varying from two to three feet in diameter. These flues are generally composed of plates of the same thickness as the outer shell of the boiler, and being of cylindrical form, they have been considered hitherto much stronger in their powers of resistance when forming an arch opposed to a uniform external pressure, than the outer shell subjected to the same force acting from the interior. This opinion was acted upon with confident security until its erroneousness was shown by direct experiment. Fig. 69 shows the ordi-

nary form of the boiler in the manufacturing districts, about 30 feet in length, 7 feet in diameter, with two internal flues *a a*, about 2 feet 8 inches in diameter. These flues as well as the external shell are generally composed of $\frac{3}{8}$ inch plates, which corresponds with a bursting pressure for the outer shell of $303\frac{1}{2}$ lbs. per square inch, which of course ought at the same time to be the collapsing pressure of the flues. This unfortunately is not the case, as, according to experiment, it is now found that the flues would give way with about 100 lbs. pressure per square inch, or the boiler would be destroyed by collapse at one-third of the bursting pressure of the shell. It is evident then that these internal flues have been constructed a great deal too weak, and without a knowledge of the true law of collapse.

It has long been a desideratum to obtain some law by which the engineer could proportion the strength of the internal flues. There have been no definite rules to guide us hitherto in proportioning the diameter, length, and thickness of plates of the flues, so as to correspond with the strength required in the boiler. And even in cases where explosions have taken place from collapse, we have, it is to be feared, too often mistaken the actual cause, from the quantity of the *débris* covering the site, and the force which has torn to pieces the outer shell.

To supply this want I undertook some time ago a long series of experiments on the laws of collapse, the results of which were made public through the Transactions of the Royal Society.* The chief laws which were ascertained may be stated as follows: —

I. *Strength as affected by length.*— The results under this head are singularly interesting and conclusive.

* The two papers on this subject are reprinted in the present volume, pp. 1—45 and 74—92. In this Lecture the results are exhibited in a more popular form for practical readers.

Within the limits of from 1·5 foot to about 10 feet in length, it is found that the strength of tubes similar in other respects and supported at the ends by rigid rings varies inversely as the length.

Thus taking the 4-inch tubes of different lengths, we have the following mean results derived from experiment: —

1. *Resistance of four-inch tubes to collapse.*

Diameter ins. (D.)	Thickness of plates, ins. (t.)	Length ins. (L.)	Collapsing pressure in lbs. (P.)	P.L.
4	·043	19	137	2603
4	·043	60	43	2580
4	·043	40	65	2600

The remarkable differences which exist in the resisting powers of the above tubes will be at once apparent. The constancy in the numbers in the last column, which represents the resisting powers of the tubes reduced to unity of length, on the assumption that the strength varies inversely as the length between the supported ends, is a proof of the substantial accuracy of the above law.

2. *Resistance of six-inch tubes to collapse.*

D.	t.	L.	P.	P.L.
6	·043	30	55	1650
6	·043	59	32	1888

In this case, as before, the product of the collapsing pressure by the length is constant, and verifies the law.

3. *Resistance of eight-inch tubes to collapse.*

D.	t.	L.	P.	P.L.
8	·043	39	32	1248
8	·043	30	39	1170

4. *Resistance of ten-inch tubes to collapse.*

D.	t.	L.	P.	P.L.
10	·043	50	19	950
10	·043	30	33	990

In the same manner all the experiments might be taken and compared, and the law found true in every case. The discrepancies are comparatively small, and, as they appear to follow no law, are evidently errors of observation arising from unavoidable defects in the construction of the tubes and the varying rigidity in the plates of iron.

Two experiments made upon actual boiler flues fixed in their proper position in boilers show that there is no great departure from the same law up to 35 feet in length.

5. *Resistance of boiler flues to collapse.*

D.	t.	L.	P.	P.L.
42	·375	35	97	3395
42	·375	25	127	3175

The longer of these two flues collapsed with 97 lbs. per square inch, whilst the shorter sustained 127 before giving way.

II. *Strength as affected by Diameter.*

A precisely similar law is found to prevail in relation to the diameter. Tubes, similar in other respects, vary in strength inversely as their diameters. Testing this law in the same manner as the last, we have the following table: —

6. *Resistance to collapse of five-feet tubes.*

D.	t.	L.	P.	P.D.
4	·043	60	43·0	172
6	·043	60	32·0	192
8	·043	60	20·8	176
10	·043	60	16·0	160
12	·043	60	12·5	150

The nearly constant numbers given in the last column, and representing the product of the diameter and collapsing pressure, or the collapsing pressure reduced to unity of diameter, verify the above law of strength.

7. *Resistance to collapse of two feet six inch tubes.*

D.	t.	L.	P.	P.D.
4	·043	30	84	336
6	·043	30	52	312
8	·043	30	39	312
10	·043	30	33	330
12	·043	30	22	264

The numbers in the last column are nearly constant.

III. *Strength as affected by thickness of Plates.*

It is found that the tubes vary in strength according to a certain power of the thickness, the index of which, taken from the mean of the experiments, is 2·19, or rather higher than the square.

$$P = 806300 \times \frac{t^{2.19}}{L.D.} \quad . \quad . \quad . \quad (1).$$

Where L is in feet. Or for convenience of calculation,

$$\log. P = 1{\cdot}5265 + 2{\cdot}19 \log. 100\, t. - \log. (LD) \quad . \quad . \quad . \quad (2).$$

With regard to cylindrical flues, the experiments indicate the necessity of an important modification of the ordinary mode of construction, in order to render them secure at the high pressures to which they are now almost constantly subjected. The weakness of flues on the present construction has already been shown. To remedy this defect, it is proposed that strong rigid rings of T, or angle iron, should be riveted at intervals along the flue, thus practically reducing its length, or in other words increasing its strength to uniformity with that of the exterior shell of the boiler. This modification, which is represented in Plate II. figs. 2 and 3, is so simple and yet so effective, that its adoption may be confidently recommended to the attention of those interested in the construction of boilers.

The following table of the proportions of boiler flues, supplementary to those given in the first series of Lectures on the proportions of the external shell, will be found worthy of attention.

TABLE *showing the proportions of internal Boiler Flues, for resisting a collapsing pressure of* 450 *lbs. per square inch.**

Diameter of Flue in ins.	Collapsing Pressure in lbs. per sq. in.	Thickness of Plates in parts of an inch.		
		For a Flue 10 feet long.	For a Flue 20 feet long.	For a Flue 30 feet long.
12	450	·291	·399	·480
18		·350	·480	·578
24		·399	·548	·659
30		·442	·607	·730
36		·480	·659	·794
42		·516	·707	·851
48		·548	·752	·905

In the above table the length of the flue must be measured between the rigid supports. In an unsupported flue, as ordinarily constructed, the length is measured between the end plates of the boiler; in a flue as proposed above between the ⊤ iron ribs. For a collapsing pressure of 450 lbs. the safe working pressure would be 75 lbs. per square inch.

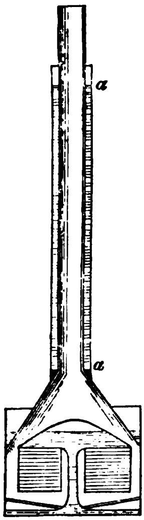
It will not be necessary to remark further on this subject, except to illustrate, by an example, the importance of these facts to the safety of the public. In the disastrous accident which attended the first trial trip of the *Great Eastern* the funnel of the boilers, which was surrounded by a water-jacket, gave way by collapse at what was probably a comparatively low pressure. This might easily have been prevented had the maker been aware of the

* This table was given in the third edition of the first series of "Useful Information."

extreme weakness of such flues when of large diameter and great length.

Fig. 70 shows the general arrangement of the boilers and funnel, covered by the jacket *a a.* The funnel, six feet in diameter, is in this case exposed to the pressure of the steam, together with that of a column of water nearly forty feet in depth, and these two forces were quite sufficient to collapse the funnel and cause the frightful explosion which occurred.

Fig. 70.



The great weakness of elliptical tubes, shown in the experiments on collapse, points out another source of danger in marine boilers, viz. the "*take-up;*" that is, the drawing in of the plates from a rectangular to a cylindrical form, where the flues join the funnel. This part requires the utmost attention, as it is not only the weakest part of the boiler from its form, unless very carefully stayed, but it is much exposed to overheating from the gases rising from the furnaces where it is above the level of the water, in which case its powers of resistance must be greatly diminished.

II. THE DENSITY OF STEAM.

If fatal accidents in the use of steam lead us to study the forms and proportions of boilers, the necessity for economy in its production and application should induce us to study minutely its properties. The knowledge of the latent heat of steam, the discovery of which had been made a short time before by Dr. Black, led Watt to his great invention of separate condensation, and since that time some of the most eminent scientific men have inves-

tigated, theoretically and experimentally, its various properties. Much has, however, yet to be done; it is true we have the experiments of Robison, Southern, Ure, Dalton, Arago and Dulong, the Franklin Institute, and last, but not least, of Regnault in France, and many others of less importance than these, so that the relations of temperature and pressure, and the amounts of latent heat, total heat, and specific heat at all temperatures have now been determined with an accuracy which we can hardly hope to see excelled. But there are other properties of which we have hardly any experimental knowledge at all. To supply some of these defects I have been engaged upon a laborious series of experiments, in conjunction with my friend Mr. Thomas Tate, with a special view to determine the relations of temperature and density of saturated steam, and the laws of the expansion of superheated steam, which have not hitherto been made the subject of any reliable experiments. These experiments, not yet completed, have not been unattended with danger, from the necessity of employing glass tubes and globes at elevated temperatures and considerable pressure. Some of these tubes exploded, and on one occasion my assistant, when reading off the mercury levels, nearly lost an eye from the fragments scattered about from a violent explosion. Every possible precaution has however been taken to obtain accurate results, and as in several respects these are new and interesting, a brief abstract may be given here in anticipation of the publication of the results in a detailed form.

For a perfect gas the law which regulates the relation between the temperature and volume, and known as Gay-Lussac's or Dalton's law, combined with the law expressing the relation of pressure and volume, known as Boyle's or Mariotte's law, is expressed in the equation, —

$$\frac{V\ P}{V_{\prime} P_{\prime}} = \frac{E + t}{E + t_{\prime}} \quad \ldots\ldots \quad (3)$$

where V is the volume of the gas at P pressure and T temperature, a constant which, according to Regnault's experiments, is 459. Now, assuming that steam follows the gaseous laws, we have, according to Dumas's experiments, $V' = 1669$, when $P' = 14{\cdot}7$ lbs. per square inch, and at a temperature $t' = 212°$ F. Making these substitutions in equation 3, we get for the volume of steam at any other temperature and pressure

$$V = 1669 \times \frac{14{\cdot}7}{P} \times \frac{459 + t}{459 + 212} = 36{\cdot}5 \, \frac{459 + t}{P} \quad . \quad . \quad . \quad . \quad . \quad (4).$$

From this well-known formula all the tables of the density of steam have hitherto been constructed on which calculations of the duty of steam-engines have been founded.

Although the accuracy of this formula, as applied to steam, has for some time been doubted, yet up to the present time no reliable direct experiments have been made to test its truth, nor are the methods hitherto employed in determining the density of gases and vapours applicable, in this case, except at the boiling temperature of the liquid under ordinary atmospheric pressure. But, on the other hand, theoretical calculations, arising out of the application of Carnot's theory, throw considerable doubt upon the accuracy of this formula, and these suspicions have been confirmed by the numerical results of Regnault's magnificent experiments upon latent heat. It is in attempting to set at rest this question by direct experiment that the present apparatus has been devised.

For permanent gases the laws of Gay-Lussac and Mariotte have been abundantly confirmed by Regnault's experiments upon air and carbonic acid. These are nearly perfect as gases, and the deviations from the gaseous laws indicated in the experiments are small, except at very enormous pressures. But with vapours the case is widely different. And as early as eight or ten years ago Dr. Joule and Professor William Thomson announced, as the result of

applying the new theory of heat to the law of Carnot, that for temperatures higher than 212° there is a very considerable deviation from the gaseous laws in the case of steam. Later, in 1855, Mr. Macquorn Rankine gave a new formula for the density of steam, independent of Gay-Lussac's law, and this confirms Mr. Thomson's surmise. Still these speculations require the confirmation of direct experiment.

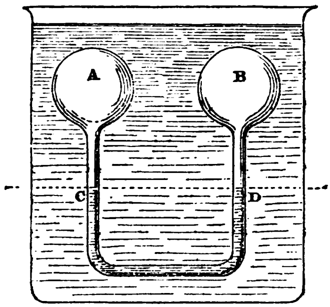
The density of steam is ascertained by placing in a glass globe, of measured capacity, and exhausted of its air, a weighed quantity of water. The globe is then placed in a bath, and raised in temperature until the entire weighed portion of water is converted into steam. The temperature at which this happens is noted, and we have thus the three elements for calculating the density, the temperature, the volume and the weight, from experimental data. The specific volume of steam, at the temperature noted, is equal to the capacity of the vessel, measured by the quantity of water it would contain, divided by the weight of water introduced into the globe. By employing different weights of water the density at any number of temperatures can be ascertained, and a new formula deduced from direct experiment.

Two difficulties, however, have to be overcome. First, the pressure of the steam renders it necessary that the glass globe should be heated in a strong and, therefore of necessity, opaque vessel. Hence the temperature at which the water is vaporised cannot be determined by direct vision. Secondly, as steam rapidly expands in volume for any increase of temperature beyond the temperature of saturation, it would in any case be impossible to decide by the unaided eye the exact temperature at which all the water became vaporised. The slightest error in deciding the temperature of saturation would vitiate the experiments, and render the results of no value.

The difficulty thus resolves itself into this, to find some other test sufficiently delicate to determine the point of saturation. This has been overcome by what may be termed the saturation gauge, and it is in this that the novelty and value of the present method consists.

The simplest form of this gauge may be illustrated by the diagram, fig. 71. Suppose two globes A and B, freed from air, and connected by the bent tube C D, which contains a portion of mercury. Suppose enough water introduced into A, to be vaporised at a temperature of

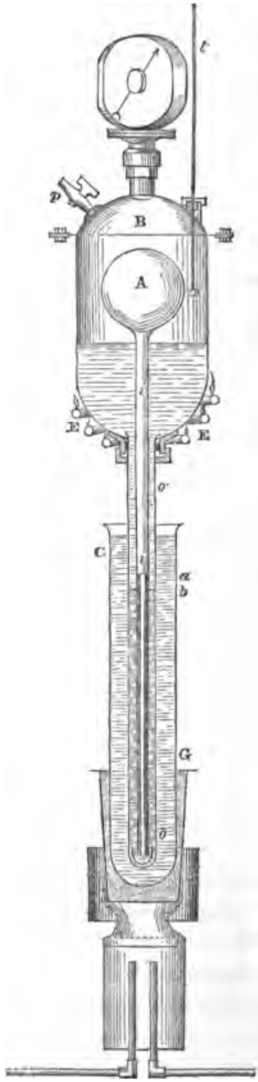
Fig. 71.



290° Fahrenheit, which corresponds with a pressure of 50 lbs.; and let any larger quantity be introduced into B; and let the water in A be separated from that in B by the mercury column C D. If now the globes be heated, the water in each will go on vaporising, and the pressure in each will go on increasing uniformly, until all the water in A is converted into steam. As soon as this point is reached the mercury columns will change their level, the column C rising nearly two inches for every degree Fahrenheit above the saturation point. The instantaneous rise of the column is the indication of the temperature of saturation. The cause of it will be perceived. As soon

as the water in A is vaporised the pressure in that globe practically ceases to increase; but as water still remains in B, the pressure in that globe increases about one pound for every degree Fahrenheit. The unequal pressure on the mercury column C D causes the rise observed. The increase of pressure resulting from vaporisation at 290° is about twelve times the corresponding increase for superheating or expansion, and for other temperatures the difference is about the same.

Fig. 72.



The application of this principle is obvious. Fig. 72 represents one of the forms of apparatus which has been constructed and employed with success. A is the measured globe with a graduated stem into which the weighed portion of water is introduced, after a Torricellian vacuum has been formed. It is placed in the copper boiler B, and its stem *i*, *i*, passes down the glass tube *o*, *o*. The boiler B is fitted with a cover, blow off cock *p*, and thermometer *t*. To heat the apparatus coils of gas jets E, E, are employed, and the temperature of the glass tube *o*, *o*, is regulated by the bath,

G, G, of oil or sulphuric acid for safety placed in a sand bath. The rise or fall of the columns of mercury *a* and *b*, of the saturation gauge is observed through the strong glass tube *o*, *o*. As soon as column *a* in the globe stem rises and *b* falls, the temperature of saturation has been reached, as the steam in the boiler B is of course always in the condition of saturation.

The experiments have been arranged and carried out with the co-operation of my friend Mr. Thomas Tate with the greatest accuracy and care, and under our own immediate direction, with the aid of my assistant, Mr. Unwin. It is hoped that the results, when pursued up to high pressures, will prove of great scientific importance and practical utility.

The experiments have been completed between the temperatures of 136° and 290° Fahrenheit, which correspond to the pressures of 2·6 lbs. or (12 lbs. less than the atmospheric pressure), and 60 lbs. per square inch, but they are being extended to higher pressures, and a special series has been instituted to ascertain the law of expansion. The results abundantly show that the vapour of water does not accurately obey the gaseous laws. We have found the density of saturated steam always greater than that given by the gaseous laws, even at low temperatures.

The following simple formula very nearly expresses the results of the experiments as to the relation of density and pressure of saturated steam, the relation between pressure and temperature having been already determined.

Let V be the specific volume of the steam, or the ratio of the volume of the steam to that of the water which produced it.

P = the pressure in inches of mercury, then we find

$$V = 25{\cdot}62 + \frac{49513}{P + {\cdot}72}. \quad \quad (5).$$

Table of Results, showing the Relation of Density and Pressure of Saturated Steam.

No.	Pressure.		Temperature, Fahr. °.	Specific Volume.		Proportional error of formula.
	In lbs. per square inch.	In inches of Mercury.		From experiment.	By formula (5).	
1	2·6	5·35	136·77	8266	8183	$+\frac{1}{100}$
2	4·3	8·62	155·33	5326	5326	0
3	4·7	9·45	159·36	4914	4900	$-\frac{1}{350}$
4	6·2	12·47	170·92	3717	3766	$+\frac{1}{74}$
5	6·3	12·61	171·48	3710	3740	$+\frac{1}{123}$
6	6·8	13·62	174·92	3433	3478	$+\frac{1}{76}$
7	8·0	16·01	182·30	3046	2985	$-\frac{1}{50}$
8	9·1	18·36	188·30	2620	2620	0
9	11·3	22·88	198·78	2146	2124	$-\frac{1}{97}$
1	26·5	53·61	242·90	941	937	$-\frac{1}{235}$
2	27·4	55·52	244·82	906	906	0
3	27·6	55·89	245·22	891	900	$+\frac{1}{100}$
4	33·1	66·84	255·50	758	758	0
5	37·8	76·20	263·14	648	669	$+\frac{1}{32}$
6	40·3	81·53	267·21	634	628	$-\frac{1}{100}$
7	41·7	84·20	269·20	604	608	$+\frac{1}{150}$
8	45·7	92·23	274·76	583	562	$-\frac{1}{29}$
9	49·4	99·60	279·42	514	519	$+\frac{1}{100}$
11	51·7	104·54	282·58	496	496	0
12	55·9	112·78	287·25	457	461	$+\frac{1}{114}$
13	60·6	122·25	292·53	432	428	$-\frac{1}{108}$
14	56·7	114·25	288·25	448	456	$+\frac{1}{56}$

The above table exhibits accurately the results at which we have arrived in regard to saturated steam; we have also obtained some results on the rate of expansion of superheated steam. These results are at present less complete than those upon saturated steam, as they do not range more than twenty degrees of temperature, in each case, above the maximum temperature of saturation. They appear, however, to show conclusively, that near the saturation point steam expands very irregularly, thus agreeing with what we know of other bodies in their physical relations at or near the point at which they change

their state of aggregation. Close to the saturation point we find a very high rate of expansion, but this rapidly declines as the steam superheats, and at no very great distance above it the rate of expansion nearly approximates to that of a perfect gas.

Thus, for instance, in experiment (6) where the point of maxim m saturation was 174°·92, between this and 180° the steam expanded at the mean rate of $\frac{1}{190}$, whereas air would have expanded $\frac{1}{634}$ only; but on continuing the superheating, the coefficient was reduced between 180° and 200° from $\frac{1}{190}$ to $\frac{1}{637}$, and for air the coefficient would have been $\frac{1}{639}$, or almost exactly the same, and this rule holds good in every experiment; a high rate of expansion close to the saturation point diminishing rapidly to a close approximation to that of air.

APPENDICES.

APPENDIX I.

ON THE RESISTANCE OF BASALT TO CRUSHING.

SINCE the paper on Stone was printed (p. 129), I have had an opportunity of testing the resistance of Basalt, or Whinstone, a rock which does not find a place in the list given in that paper. The following results were obtained: —

Specimen 1.

Height 1·25 inches.
Area 1·22 × 1·24 = 1·5128 sq. inches.
Fractured with a weight of 17,418 lbs.
Crushed with 17,866 lbs.
Equivalent to 11,755 lbs. per sq. inch.

Specimen 2.

Height 1·38 inches.
Area 1·26 × 1·25 = 1·5750 sq. inches.
Fractured with 17,418 lbs.
Crushed with 19,914 lbs.
Equivalent to 12,643 lbs. per sq. inch.

Specimen 3.

Height 1·38 inches.
Area 1·26 × 1·26 inches = 1·5876 sq. inches.
Crushed suddenly with 18,274 lbs.
Equivalent to 11,510 lbs. per sq. inch.

All the above specimens fractured by vertical fissures splitting up into thin prisms, wedge-shaped usually at one end. The mean crushing resistance of the above specimens is therefore—

		lbs.
	(1.)	11,755
	(2.)	12,643
	(3.)	11,510
Mean . . .		11,970 = 5·3437 tons per sq. inch.

The mean of three experiments on Granite gave 11,565 lbs. per sq. inch for the crushing resistance of that substance, and for Grauwacke from Penmaenmawr it was found to be 16,893 lbs. per sq. inch. The Irish Basalt is, therefore, equal in strength to the Granite, but inferior to the Grauwacke in the ratio of 1·0 to 1·4.

APPENDIX II.

MR. GRANTHAM'S VIEWS ON THE STRENGTH OR IRON SHIPS.

SINCE the above Lecture was written I have had an opportunity of reading Mr. Grantham's paper on the Strength of Iron Ships, and it is gratifying to me to find that that gentleman takes precisely the same views as I have expressed above in regard to the weakness of our present construction of iron vessels. He adduces an additional reason for increasing the strength of the upper part, viz. the tendency of very long vessels to hog. "It is well known," he says, "that many iron steamboats are now employed in carrying heavy cargoes, whose length is eight times the beam, and I have frequently examined one vessel, that has sailed round the world, whose length is nine times the beam; nor is there anything in these vessels which would lead to the conclusion that such proportions are excessive. On the contrary, with improved construction, a much greater length may be ultimately attained,

especially in large vessels. The maximum of length in wooden ships has often been attained, and probably a proportion of six times the beam has seldom been exceeded, without showing unfavourable results, when heavy weights had to be carried.

"I shall best explain my views by describing the result of a calculation I lately made for the purpose of giving evidence in an important trial. The object sought was, to ascertain whether a vessel loaded as this was would rise or fall at the ends, or, in popular language, whether she would *sag* or *hog*. This ship was built of timber, with fine lines, rather light ends, and the cargo very evenly distributed; she was 225 feet long, and 42 feet beam. For the sake of the calculation the longitudinal elevation was divided into ten equal parts. The displacement of each section, the weight of the ship, and cargo also of each section, were calculated, when it was found that the ends were depressed by a force of 220 tons, and thus threw a strain on the centre equal to that weight multiplied by the leverage.

"The tendency, as above observed, is to build iron ships, especially iron steamers, much longer and finer than this vessel; it is clear that the excess of weight over displacement at the ends will increase in the same ratio, unless precautions are taken to reduce the weight there. Great attention has been paid to this subject in the timber built steamers of America; and it is found that vessels which to us appear dangerous, from the extreme height of deck-houses and machinery amidships, are plying throughout the year on their wild Atlantic coast with comparative safety.

"Now it is quite clear that a vessel should be so constructed, and, if possible, so loaded, that when in smooth water the weight should as nearly as possible correspond with the displacement of every portion."

In regard to the distribution of material in ships as now constructed, Mr. Grantham expresses himself strongly. "I think I shall best serve the cause I have so long advocated, by saying distinctly, that in my opinion a large proportion of the material now used in iron ships is worse than useless." . . . . "Experience has confirmed the impression which would arise

upon any unbiassed mind, on reading the specifications of many of our finest ships, viz. that they would first show weakness in the centre, the scantling given to the ends being in general out of all proportion to that of the midships." . . . . . "The *Great Eastern* is perhaps the only large vessel where this question has been fairly dealt with, the only one where the girder principle has been effectually applied, and though the exact form there adopted could only be applied in very large ships, yet the principle is correct, and probably the proportions also."

APPENDIX III.

LETTERS TO THE "TIMES" ON THE WRECK OF THE ROYAL CHARTER.

I.—To the Editor of the Times.

SIR,—Among the many and mighty inventions and adaptations which have contributed to make this country and this age famous, a conspicuous place must be given to the application of iron to shipbuilding. Without it England's mercantile marine could scarcely have kept pace with the marvellous growth of her commerce, and oceanic steam navigation would yet have been in its infancy. Even Brunel's genius would have quailed in attempting the construction of the Great Ship in any other material; and it is scarcely too much to say that the abundance and richness of the ferruginous ores which are found in this island, and the facilities for their reduction placed to our hands by nature, compelled our naval constructors to direct their attention to the use of manufactured iron in building vessels.

The iron ship, when well built, is indeed stronger, safer, and more durable than any other, and yet if we search the records of those disasters to which all seagoing ships are exposed, it will be found that the most destructive and appalling have occurred in iron bottoms. I need only call to mind the wreck

of the *Birkenhead*, which will find a place in history as the scene where the disciplined bravery and devotion of our soldiers were nowhere more conspicuously displayed, and that awful and heartrending catastrophe which within the last few days has carried sorrow and anguish into hundreds of homes. Yes, while the hearts of relatives are yet bleeding, and the public is stunned with the immensity and suddenness of its loss, while many would try to bury their grief in oblivion, and others would prefer to contemplate in silence such an illustration of the mysterious ends of Providence, I conceive that the lessons which the loss of the *Royal Charter* is calculated to afford ought not to be overlooked, and that the causes of a wreck so sudden and so complete should be most promptly and searchingly investigated.

I would, therefore, very earnestly and prominently bring under the notice of your readers certain general features and practices in the construction of iron vessels which in my opinion are in the last degree dangerous and reprehensible. It would seem to commend itself to the common sense of every man, that in building an iron sailing or steamship which is to be subjected to all the strains and buffetings of tempest-tossed seas, which will be freighted with hundreds of human beings and the most precious cargoes, and which must run the risks of collisions and strandings, none other than the very best and strongest materials should be employed. The toughest iron, the best seasoned spars, and the stoutest planks and ropes should alone find places in such a venture. But in our ordinary every-day practice is this the case? Is not any kind of iron thought good enough to build a ship with? What is the meaning of "boat plates" being the lowest priced in any ironmaker's list? If we pay 25*l.* or 30*l.* a ton for the plates of which a locomotive boiler is made, why should we give only 8*l.* 10*s.* or 9*l.* per ton for those of which a ship is built? If safety can only be bought at the high price in the one case, are we not courting disaster with the low price in the other? Who will draw the fine line of distinction in moral responsibility between the directors of a railway company who should take your fare, place you in a comfortable first-class carriage,

and drive you at forty miles an hour over a viaduct which was miserably insecure, and the owners of vessels who send passengers to sea in ships sheathed with plates which are as brittle as glass? The only answer to this question in the way of excuse is, I fear, that most men are really and truly ignorant of the facts. In the eyes of the merchant in London or Liverpool, who orders the building of a ship, iron is iron. He probably does not know that in this material there are as many shades of quality as there are in the wines or fruits which all bear one common name, and yet I am within the mark when I say that he might by paying 2*l.* or 3*l.* per ton increased price upon the plates forming the outward sheathing of his ship immensely increase the vessel's strength and durability.

With good well-worked plates, where the fibre of the iron is ductile and tenacious, and where these plates are well and judiciously fastened together, no vessel, even if wrecked in such a gale as that of last Tuesday, would break to pieces so suddenly and so utterly as the *Royal Charter* seems to have done.

But built of the "boat plates" of the present day, God help the human freight of the ship that strikes upon a rocky shore!

I would therefore advise shipowners when contracting for new vessels, instead of being satisfied with a specification which provides good ordinary "boat plates" to be used, and which are, in fact, about the most rubbishy quality of iron which is made, to insist that the sheathing should all be of best best, or double-worked quality. In a vessel of 1000 tons it would not increase the cost 500*l.*, and the value is gained in the greater strength and durability of the ship, to say nothing of the lives that it may possibly save.

Further, I would caution all well-disposed shipowners to look with great suspicion upon the cheap offers which are constantly laid before them as temptations to order ships. To any one conversant with a ship's value, what other construction can be put upon a contract for a vessel of 1000 tons, with the most expensive outfit, for 13*l.*, or 13*l.* 10*s.*, or even 14*l.* per ton measurement ready for sea, than that the builder means to

employ bad materials and scamp his work? He begins upon such an order with a determination either to cheat his customer or cheat his creditors. But such vessels are built on the Clyde, the Tyne, and elsewhere, and I maintain that the shipowner, in buying them, shares with the builder the moral responsibility of a great guiltiness, for they are deliberately launched and freighted to go to the bottom.

I am, Sir, your faithful servant,

AMICUS.

Manchester, Oct. 31.

II.—To the Editor of The Times.

SIR,—In noticing the letter on iron shipbuilding which I addressed to you soon after the wreck of the Royal Charter, you most correctly observed that in making the statements I did it was neither my intention nor my wish to point any particular charge against the owners or the builders of that unfortunate ship. To have done so while the inquiry before the coroner's jury was unfinished, and when we were promised an official investigation by officers appointed by the Board of Trade into the causes of the disaster, would have been most inconsiderate and most unfair. I therefore confined my charges to certain hurtful practices both in the construction and the purchase of iron ships, which may be said to be of almost general pertinence, and therefore well worthy of attentive consideration. These evils are—first, the frequent use of the worst quality of iron made, and called "boat iron," in the construction of ships; and, second, the frightful risks to life and property which the public is called upon to sustain in consequence of a competition among shipbuilders, encouraged by shipbuyers, wherein price alone is considered, and quality (which includes durability and safety) is entirely ignored.

While dealing with these general questions I ventured,

however, to express an opinion that no properly proportioned vessel, if built of well-worked ductile iron plates, and well fastened together, would have shivered to atoms so suddenly as the Royal Charter seems to have done, and to this opinion I will still firmly hold for the sake of the interests involved and the thousands of lives now afloat in our iron ships.

It is true that the Welsh jury found a verdict acquitting everybody of blame, and the able report of Mr. Mansfield, which I have just read most carefully, states that from the evidence he had arrived at the conclusion that the *Royal Charter* was, at the least, fully equal in strength to the average ships of her class at the same date (1855).

I do not quarrel with either verdict or report. Upon the evidence brought before the two tribunals the decisions could not have been different. But if that evidence had been made more comprehensive; if the captain or others in authority had been saved to tell us of the ship's behaviour in heavy weather; if we had had more general and extensive tests of the strength of the ship's material; if some calculations had been furnished of her strength considering her hull as a beam supported in the middle and unsupported at its ends, which must have been very nearly the ship's position when she parted amidships; and if we had been informed whether the plates used in her construction were really "boat plates," or "best plates," and where they had been made, the public would have been inclined to attach greater importance to the conclusions arrived at. Because, if those conclusions were indisputable, I confess they would give rise in my mind to many most anxious reflections—reflections which would be so painful to myself and to others, that I would stifle their expression rather than create alarm by their publication.

We are told that the *Royal Charter* was fully equal in strength to the ships of her class. Am I, therefore, to believe that every iron ship which shall drift during a storm on to a rocky shore, or which shall sustain an equally severe shock by collision in mid-ocean with another ship, must of necessity tumble to pieces in the short time — the few awful minutes —

which sufficed to hurry the *Royal Charter's* wretched passengers and ship's company into eternity? Am I to believe that there is no hope for the human freight of such a ship stranded within fifty yards of land, and with a hawser already sent on shore — that it is their inevitable fate to be engulfed by the angry waters, struggling and clinging together? Are sea-voyagers to be told that, of all the thousands of iron ships afloat, the fate of every one is almost instantaneous and utter destruction, should she strike upon some hidden reef?

Surely these are unnecessary alarms and suspicions to entertain, even after so terrible a tragedy as the wreck in Moelfra Bay; and yet a belief in them is a legitimate deduction from the admission of the *Royal Charter* being, for her class, a vessel of fully average strength.

And surely it is a more probable, a more charitable, and a more comfortable inference, that some hidden source of weakness in the materials or in the construction of the ill-fated ship itself was the cause of that sudden and terrible crash, than that so many we love and so much that we value are now and always intrusted in fragile and unsafe ships.

There are not wanting many and pertinent examples of wrecks to iron ships which point to the very opposite conclusion, proving their strength and safety, and showing how tenaciously they will hold together under severe and lengthened strains. The *Great Britain*, it will be remembered, was left bumping upon the rocks in Dundrum Bay during a whole winter, and even in that exposed position was thought so safe, and so far from destruction, that her crew remained on board. In the case of the *Vanguard*, wrecked on the west coast of Ireland, and exposed consequently to the full swell of the Atlantic, it appears she remained in a position in which, from midships to the stern, she was entirely unsupported, and yet was so little injured that, in the words of one who went over to examine her, "although beating hard upon the rocks for so many days, no part of her engines was deranged, and they were kept constantly at work." Again, the *Royal George*, an iron steamer running between Liverpool and Glasgow, and a

vessel of unusual length compared to her beam, got on a rock near Greenock at high water, and as the tide receded it was found she rested nearly on her centre, with both ends entirely unsupported. No vessel could have been subjected to a severer strain than this, and yet she also was hauled off at the next tide entirely uninjured. I could adduce numerous other instances to prove my point that well-constructed iron ships are very safe — in fact, safer than any wooden ships can be made, because the iron ship is by the riveting and proportioning of the plates made into a firm continuous mass of uniform strength; whereas a wooden ship is composed of innumerable pieces, which at best can only be imperfectly joined together. But then greater circumspection is required in the selection of the material for the iron than for the wooden vessel. A shaky or rotten piece of oak, teak, or elm is easily detected; and if a shipbuilder use deal where oak should be placed, at least his dishonesty is readily discovered. But, if I may be permitted the paradox, iron is not always iron. It is sometimes rubbish, and in this category I would unhesitatingly place all "boat plates." It is not that even in these inferior plates pieces may not be found which shall come up to and even surpass Mr. Fairbairn's standard of the average tenacity of good Staffordshire plate; but, being made chiefly from cinder iron, it is their *inequality* and *uncertainty* which is most to be dreaded. The strength of the whole is that of the weakest part, and when I tell you that out of the same "boat plate," or iron of that quality, two pieces have been taken, one of which sustained 22 tons to the square inch of section, while the other failed at 5 tons, I have said enough to show why this dangerous material should be at once discarded in building ships, and the price of "best plates" be paid to ensure the exclusion of cinder iron from their manufacture. Boat plates are shams. They are got up to deceive by appearances. Smooth and well-looking on the surface, the source of mischief lies hidden underneath — rotten at the core, like the grub-eaten fruit whose tempting skin conceals the tiny hole by which the insect has entered. But this iron is a curse as well as a decep-

tion, for while you may be angered at the Yankee who has sold you wooden nutmegs, or the grocer who sands his sugar, or the petty swindler who sells you 100 yards of sewing cotton "warranted" 200, I know no words strong enough to condemn the practice of makers and buyers alike, who in structures where the safety of life and limb is at stake, will willingly and knowingly, and for gain's sake alone, imperil the existence of their fellow-creatures.

I am, Sir, your faithful servant,

AMICUS.

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